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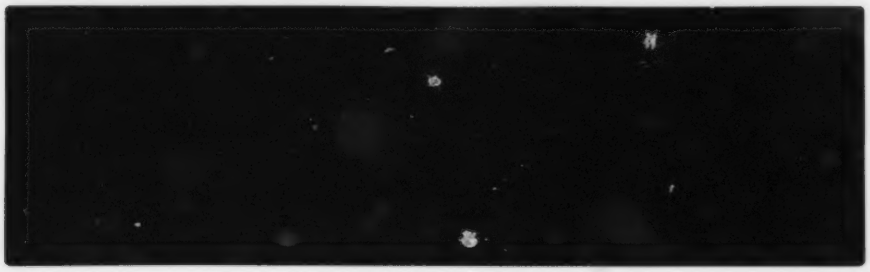

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SCALE EFFECTS TESTING ON

ROCK SAMPLES FROM LAC DU BONNET, MANITOBA: REPORT #1

R. Jackson

MRL 89-39 (TR)

March, 1989

86 pages

86pp

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SCALE EFFECTS TESTING ON ROCK SAMPLES FROM LAC DU BONNET, MANITOBA: REPORT #1

by

Rand Jackson*

ABSTRACT

Compressive and shear wave velocity measurements, as well as uniaxial compression testing, were conducted on samples of gray granite obtained from the site of Atomic Energy of Canada Ltd.'s underground research laboratory (URL). Four specimen diameters ranging from 33mm to 141mm were studied in an attempt to determine what, if any, were the effects of scale on the predominant rock type in the vicinity of the URL.

Samples up to 63mm, while showing some variation, indicated no trends with increasing specimen size for the properties determined as part of this study. This is attributed to the relative homogeneity of the gray Pinawa granite and problems associated with specimen preparation and specimen/machine interaction. Definite trends of decreasing uniaxial compressive strength and tangent modulus of elasticity were noted as specimen diameter increased from 63mm to 141mm. However, Poisson's ratio determined at 50% of failure load showed little dependence on sample size.

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Keywords

Rock Properties, Mechanical, Young's Tangent Modulus, Poisson's Ratio, Uniaxial Compressive Strength, Velocity, Lac du Bonnet, Scale Effects

ETUDE DES EFFETS D'ÉCHELLE SUR DES ÉCHANTILLONS DE ROCHE PROVENANT DE LAC DU BONNET (MANITOBA): RAPPORT #1

par

Rand Jackson*

RÉSUMÉ

Des mesures de vitesse des ondes de compression et de cisaillement ainsi que des essais de compression uniaxiale ont été réalisés sur des échantillons de granite gris provenant du site du Laboratoire de recherche souterraine de l'Énergie atomique du Canada ltée. On a étudié quatre diamètres d'échantillon variant de 33 mm à 141 mm dans le but de déterminer les effets d'échelle éventuels sur le type de roche qui prédomine dans les environs du Laboratoire de recherche souterraine.

Jusqu'à 63 mm, les échantillons présentaient quelques variations, mais on n'à observé aucune tendance en ce qui concerne les propriétés déterminées dans le cadre de la présente étude lorsque la taille de l'échantillon augmentait. Ce résultat a été attribué à la relative homogénéité du granite gris de Pinawa et à des problèmes associés à la préparation de l'échantillon et à l'interaction échantillon/machine. Lorsque le diamètre de l'échantillon augmentait de 63 mm à 141 mm, on a observé une nette tendance à la diminuation de la résistance à la compression uniaxiale et du module d'élasticité tangentiel. Toutefois, le coefficient de Poisson correspondant à 50% de défaillances s'est révélé très peu dépendant de la taille de l'échantillon.

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Mots clés

Propriétés des roches, mécanique, module tangentiel de Young, coefficient de Poisson, résistance à la compression uniaxiale, vitesse, Lac du Bonnet, effets d'échelle

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INTRODUCTION

As part of the Canadian Nuclear Fuel Waste Management Project (CNFWMP), Atomic Energy of Canada Limited is characterizing various rock formations within the Canadian Shield to determine their suitability for the long term disposal of high level wastes. The program also includes the construction of an underground research laboratory (URL) near Pinawa, Manitoba to provide an opportunity for extensive in situ investigations. In preparation for these investigations, considerable laboratory testing has been conducted to supply numerical modellers with input data for use in predicting possible ground movement and changes in the stress field resulting from excavation and anticipated thermal loading.

The vast majority of laboratory testing, however, has utilized 45mm diameter specimens while in situ experiments will involve much greater volumes of rock. Because of this, it becomes important to quantify what, if any, scale effects influence the strength and deformational properties of the Pinawa granite. Towards this end, a preliminary investigation has been conducted to study the effect of specimen size on the ambient temperature uniaxial mechanical properties of the gray granite found on the 220 m level of the URL.

This report presents the results of the program, offers some possible explanations for the observed behaviour and recommends what additional work might be warranted.

IDENTIFICATION OF SPECIMENS AND TESTS

Forty five samples originating from boreholes 209-018-EXT3, 209-025-SV2, 209-017-SMF1, 209-015-SMR2 and 209-055-OC3 were prepared for uniaxial compression testing. Of these, fourteen 33mm diameter, eleven 45mm diameter, eleven 63mm diameter and nine 141mm diameter specimens were tested. Table 1 provides a summary of the borehole number, specimen depth, dimensions and density. The following properties were determined for the samples listed;

1) compressive wave velocity
2) shear wave velocity
3) dynamic shear modulus, G_d
4) dynamic Young's modulus, E_d
5) Poisson's ratio (determined using velocity data)
6) uniaxial compressive strength
7) Poisson's ratio
8) tangent modulus of elasticity, E_t

Table 1: Summary of Specimen Dimensions

Specimen identification	Sample depth (m)	Length (mm)	Diameter (mm)	Mass (g)	Density (g/cm^3)
209-018-EXT3	8.74	66.85	33.32	153.90	2.64
	8.81	66.81	33.34	154.09	2.64
	8.89	68.04	33.32	156.90	2.64
	8.97	67.48	33.32	155.84	2.65
	9.04	68.09	33.33	157.23	2.65
	11.19	68.61	33.32	158.08	2.64
	11.33	67.72	33.32	156.15	2.64
	11.41	68.18	33.33	157.27	2.64
	11.53	67.49	33.33	156.17	2.65
	11.62	66.71	33.33	154.20	2.65
	11.69	68.23	33.36	157.90	2.65
	11.86	68.13	33.34	157.80	2.65
	11.93	66.96	33.34	155.05	2.65
	12.02	70.01	33.34	162.11	2.65
209-025-SV2	6.15	92.51	45.04	387.70	2.63
	6.25	95.07	45.05	400.09	2.64
	6.45	93.76	45.05	393.85	2.64
	6.68	95.87	45.05	403.72	2.64
	6.78	95.14	45.05	400.13	2.64
	6.91	95.80	45.04	402.44	2.64
	7.03	95.54	45.05	400.77	2.63
	7.15	97.08	45.06	408.49	2.64
	7.24	95.30	45.05	401.25	2.64
	7.65	96.66	45.05	403.80	2.62
	7.75	94.99	45.03	397.14	2.63

Table 1: (cont'd)

Specimen identification	Sample depth (m)	Length (mm)	Diameter (mm)	Mass (g)	Density (g/cm^3)
209-017-SMF1	1.33	134.69	62.97	1103.85	2.63
	1.75	133.48	63.21	1107.28	2.64
	1.89	135.09	63.22	1120.26	2.64
	2.45	133.09	63.23	1103.24	2.64
	2.59	136.40	63.23	1129.94	2.64
	2.87	135.49	63.21	1121.88	2.64
209-015-SMR2	0.93	130.60	63.24	1080.53	2.63
	2.18	135.16	63.20	1115.59	2.63
	2.33	136.37	63.20	1121.91	2.62
	2.60	135.45	63.21	1122.00	2.64
209-055-OC3	4.82	305.41	141.12	12604.0	2.64
	5.46	306.43	141.44	12767.4	2.65
	5.80	318.31	142.46	13343.6	2.63
	6.13	302.77	142.56	12716.2	2.63
	6.44	304.62	140.58	12549.5	2.65
	8.76	309.37	140.20	12584.2	2.63
	9.09	305.33	140.68	12522.9	2.64
	9.41	311.76	141.06	12807.6	2.63

DESCRIPTION OF TEST MEASUREMENTS

Compression and shear wave velocity measurements were carried out on samples prior to being gauged for elastic deformation measurement. The testing equipment consisted of: transmitting and receiving platens containing piezoelectric transducers, a high voltage pulse generator, a signal amplifier and a Tektronix Type 555 dual beam oscilloscope equipped with delay sweep and a time base resolution of 0.01 micro-seconds.

For an outline of the strain gauge installation and measurement procedure, the reader is referred to Technical Data 303410-M01/78 (2). The two Phillips PR 9302 strain bridges referred to in that document were replaced, in the present study, by two

Bruel and Kjaer Type 1526 strain indicators. Linear variable differential transducers (LVDT's) were also utilized to provide redundant measurements of axial deformation. Tests were conducted on an MTS 880 Rock Mechanics Test System with analogue signals from each measuring circuit being recorded every three seconds. Samples were compressed in load control at a rate of 1 kN/sec up to a circumferential displacement of 0.02 mm. Control was subsequently governed such that a circumferential strain rate of $77 * 10^{-6}$ mm/mm/sec was maintained. This method of loading enabled the operator to avoid the violent brittle fracture usually associated with high strength rocks such as the Pinawa granite.

DATA TREATMENT

The compressional and shear wave velocities were determined by dividing the specimen length by the wave travel time through the specimen. The dynamic properties were then calculated using the following equations (3);

Dynamic Young's Modulus

$$E_d = \frac{\rho V_s^2(3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \tag{1}$$

where; E_d =dynamic Young's modulus
V_s =shear wave velocity
V_p =compressional wave velocity
ρ =density

Dynamic Shear Modulus

$$G_d = \rho V_s^2 \tag{2}$$

where; G_d =dynamic shear modulus
V_s =shear wave velocity
ρ =density

Poisson's Ratio (based on velocity data)

$$\nu_d = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \tag{3}$$

where; ν_d =Poisson's ratio
V_s =shear wave velocity
V_p =compressional wave velocity

Stress/strain curves were computer generated using analog outputs from the strain bridges and press. The tangent modulus of elasticity (E_t) was calculated for each sample by determining the slope of the tangent to the axial strain curve at stress levels of 10, 20, 30, 40, 50 and 60 MPa and 10%, 20%, 30%, 40%, 50% and 75% of the failure load. The ultimate compressive strength of each sample was calculated by dividing the sample failure load by the sample's cross-sectional area. The ratio of the tangent to the axial strain curve to the tangent to the transverse strain curve at 50% failure load was used to determine the sample's Poisson's ratio (ν).

DATA SUMMARY

Tables 2 through 5 provide a summary of ultrasonic velocity measurements and the associated dynamic properties for the 33, 45, 63 and 141mm diameter specimens, respectively. Tables 6 through 9 offer summaries of the uniaxial mechanical properties including compressive strength, tangent modulus of elasticity and Poisson's ratio for the same specimen diameters. Table 10 contains means and standard deviations of the velocity and dynamic property measurements while Table 11 contains similar treatments of the uniaxial mechanical property data.

Figures 1 through 3 illustrate plots of P and S wave velocities, dynamic shear and Young's moduli and dynamic Poisson's ratio versus specimen diameter, respectively. Figure 4 shows the variation of the uniaxial compressive strength with specimen diameter. Figure 5 presents the same data as Figure 4 with the exception of data used for the 45mm diameter specimens. Here, strength data from samples obtained from Room 206 were used for the purposes of comparison. Figures 6 through 17 contain plots of the tangent moduli at stress levels of 10, 20, 30, 40, 50, 60 MPa and 10%, 20%, 30%, 40%, 50% and 75% of ultimate strength versus specimen diameter, respectively. Figure 18 shows changes in Poisson's ratio associated with specimen diameter. Figure 19 represents pseudo-stress/strain curves generated utilizing the mean tangent moduli determined for the stress levels just mentioned and the mean compressive strengths for each specimen diameter. Figures 20 through 61 are the axial and circumferential stress/strain curves for the individual test specimens.

OBSERVATIONS AND CONCLUSIONS

The propagation of longitudinal or compressive waves in rock is dependent on several factors including: rock type, texture, density, porosity, stress, anisotropy, water content and temperature (Lama and Vutukuri, 1978). In a relatively homogeneous,

isotropic rock such as the Pinawa gray granite, most, if not all, of these could be considered to be held constant regardless of sample size. Specimen diameter should not, therefore, be seen to have much effect on its dynamic properties. This is reflected in the apparently random distributions of velocities and dynamic moduli versus specimen diameter illustrated in Figures 1 and 2. It is interesting to note, however, that the dynamic Poisson's ratios determined using equation 3 consistently decrease with increasing sample size.

Historically, the effect of sample size on the mechanical properties of rock has been attributed to two competing mechanisms (Vutukuri, Lama and Saluja, 1974). On one hand, an increase in specimen volume results in the increased probability that critical flaws exist in the sample causing an apparent lowering of strength. On the other, as specimen diameter decreases, the larger surface area to volume ratio causes imperfections due to sample preparation and testing to have greater impact, generally resulting in undue stress concentrations and a lowering of the compressive strength. While the former depends on inherent properties of the rock mass, the latter is more a result of specimen handling and the interaction between it and the testing apparatus.

Solely from the results of this investigation, it is difficult to discern any trends relating the effect of scale to the uniaxial compressive strength of the gray Pinawa granite. Mean strengths determined for the 45mm and 141mm diameter sample suites were both 171 MPa ($\sigma_{45mm} = 9$, $\sigma_{141mm} = 3$) while the 33mm and 63mm diameter samples exhibited values of 195 ($\sigma_{33mm} = 7$) and 199 MPa ($\sigma_{63mm} = 11$), respectively. However, anisotropy studies involving uniaxial testing (Jackson, 1987, 1988) were conducted using 45mm diameter specimens obtained from Room 206 which is located on the same operating level as the Room 209 specimens used for this investigation. This considerably larger sample population (n=39) yielded a mean uniaxial compressive strength of 193 MPa ($\sigma = 21$). As Figure 5 indicates, this brings the 45mm results well within the range of values determined for the 33mm and 63mm specimens.

Hodgson and Cook (1970) found no scale effect in quartzite and shale specimens up to 15cm in diameter when special precautions were taken to ensure uniform loading. Hoskins and Horino (1969) observed net increases in strength for Kansas limestone, Carthage marble and Longmont sandstone up to specimen diameters of 2 to 3 in. after which increasing specimen diameter resulted in a decrease in strength. Salida granite, however, exhibited a continuous decrease in strength with increasing specimen diameter. Lundborg (1967) and Burkartz and Kreuger (1968) also noted decreases in strength with increasing sample size for granitic specimens although to varying degrees.

These, as well as the results of this program, indicate that unless extraordinary means are employed it is difficult to determine the contribution of any one mechanism

to the behaviour of specimens below the 63mm diameter range. It is apparent, however, that the increase in volume in going from 63mm to 141mm diameter specimens has resulted in a 14% decrease in strength which, in turn, is likely caused by an increased incidence of critically oriented micro-cracks and fractures. The existence of only two valid points for a scale effects curve, unfortunately, makes it difficult to assign any type of relationship between uniaxial compressive strength and specimen size.

Scale effects on uniaxial strength, while not completely understood, have been studied extensively. A literature search of size influence on deformation characteristics, however, reveals very little. What exists, in general, indicates that there is some reduction in the elastic modulus with increasing specimen size as is the case in the present study. (Lama, 1970, Hudson, Brown and Fairhurst, 1971).

When analyzing the stress/strain data, the tangent moduli of elasticity were determined at stress levels of 10, 20, 30, 40, 50, and 60 MPa and at 10%, 20%, 30%, 40%, 50% and 75% of the failure stress. This data treatment made it possible to construct a form of pseudo-stress/strain curve to represent the mean mechanical behaviour for each specimen diameter.

As Figure 18 indicates, there appears to be little difference in the stress/strain behaviours of the 33mm and 45mm specimens. As the specimen diameter increases beyond 45mm, however, a consistent reduction in tangent moduli due to increased specimen size is evident. At 10 and 20 MPa, reductions in moduli of 30% and 26% were observed as the specimen diameter increased from 45mm to 141mm. With increasing stress, the mean moduli of the four diameters tend to converge until a maximum difference of only 12% was noted at 60 MPa.

This behaviour appears to be consistent with the theory that strength reduction is due to the increased probability of unfavourably oriented micro-cracks in larger specimens. The existence of open micro-cracks will also result in increased specimen deformation and, therefore, reduced moduli especially at lower stress levels. As the zone of linear-elastic behaviour is approached, differences in moduli diminish as one might expect in a relatively homogeneous rock like the Pinawa granite. It might also be expected that confining pressure would tend to reduce the effect of crack closure on the observed moduli.

Poisson's ratio (ν) was determined for each sample at 50% of its failure load. At this stress level, the influence of crack closure or propagation on the deformational properties of hard rock is minimal (Lama and Vutukuri, 1978). One could then expect that the effect of scale on the observed Poisson's ratio of the Pinawa granite would likewise be negligible. Measurements indicate, however, that there is a considerable

26% decrease in ν as sample diameter increases from 33mm to 45mm (0.42 and 0.31, respectively) (Figure 18).

While the 33mm diameter specimens might be expected to exhibit the largest Poisson's ratio of those tested, it seems unlikely that intrinsic properties of the rock account for the observed values. More likely, deficiencies in the measuring system associated with strain gauge size and specimen length and diameter are the cause of the anomalous values. Again, the contribution of any single mechanism to this behaviour would be difficult to quantify but, from the negligible differences in the remaining results, it seems reasonable to assume that Poisson's ratio of the gray Pinawa granite is little affected by scale for the specimen sizes used for the CNFWMP.

In general, it appears that for samples below 63mm in diameter, there are a number of influences determining the observed mechanical behaviour which are difficult to quantify in the analyses. Also, samples used for the 45mm diameter testing may not have been representative of the rock mass as the strength values indicate. Definite trends of decreasing uniaxial compressive strength and tangent modulus of elasticity, however, are evident as the sample diameter increases from 63mm to 141mm. Unfortunately, while two point are sufficient to indicate a trend, they are not useful in determining a precise relationship between sample size and mechanical properties. It is recommended, therefore, that two additional sample diameters of 100mm and 200mm be tested as well as a re-examination of the Room 206-45mm data to provide reliable information for that data point.

Table 2 - Summary of Ultrasonic Velocity Properties: 33mm Diameter Specimens

Drill Hole	Sample Depth (m)	P-wave Velocty (km/sec)	S-wave Velocity (km/sec)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
209-018-EXT3	8.74	4.71	2.27	13.56	36.58	0.35
	8.81	4.77	2.30	14.01	37.78	0.35
	8.89	4.60	2.43	15.59	40.72	0.31
	8.97	4.89	2.30	14.06	38.16	0.36
	9.04	4.83	2.35	14.61	39.30	0.34
	11.19	4.87	2.34	14.48	39.06	0.35
	11.33	4.74	2.28	13.72	37.03	0.35
	11.41	4.70	2.38	14.90	39.59	0.33
	11.53	4.79	2.24	13.32	36.22	0.36
	11.62	4.66	2.22	13.02	35.26	0.35
	11.69	4.77	2.37	14.87	39.75	0.34
	11.86	4.83	2.31	14.13	38.22	0.35
	11.93	4.96	2.18	12.61	34.80	0.38
	12.02	4.80	2.26	13.52	36.70	0.36

Table 3 - Summary of Ultrasonic Velocity Properties: 45mm Diameter Specimens

Drill Hole	Sample Depth (m)	P-wave Velocty (km/sec)	S-wave Velocity (km/sec)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
209-025-SV2	6.15	4.89	2.47	16.09	42.76	0.33
	6.25	4.80	2.64	18.46	47.35	0.28
	6.45	4.78	2.62	18.11	46.57	0.29
	6.68	4.94	2.82	20.93	52.73	0.26
	6.78	4.78	2.75	19.96	50.02	0.25
	6.91	4.74	2.65	18.59	47.30	0.27
	7.03	4.62	2.69	19.00	47.24	0.24
	7.15	4.95	2.66	18.68	48.46	0.30
	7.24	4.84	2.68	18.97	48.51	0.28
	7.65	4.52	2.70	19.10	46.68	0.22
	7.75	4.54	2.53	16.88	43.02	0.28

Table 4 - Summary of Ultrasonic Velocity Properties: 63mm Diameter Specimens

Drill Hole	Sample Depth (m)	P-wave Velocty (km/sec)	S-wave Velocity (km/sec)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
209-017-SMF1	1.33	3.54	2.23	13.13	30.78	0.17
	1.75	3.65	2.18	12.56	30.68	0.22
	1.89	3.48	2.14	12.14	29.00	0.19
	2.45	3.56	2.23	13.08	30.83	0.18
	2.59	3.71	2.23	13.11	31.91	0.22
	2.87	3.51	2.12	11.83	28.73	0.21
209-015-SMR2	0.93	3.80	2.13	11.90	30.25	0.27
	2.18	3.67	2.19	12.66	30.96	0.22
	2.33	3.50	2.17	12.35	29.31	0.19
	2.60	3.41	2.14	12.13	28.48	0.17

Table 5 - Summary of Ultrasonic Velocity Properties: 141mm Diameter Specimens

Drill Hole	Sample Depth (m)	P-wave Velocty (km/sec)	S-wave Velocity (km/sec)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
209-055-OC3	4.82	4.44	2.92	22.56	50.39	0.12
	5.15	4.11	2.73	19.97	43.55	0.11
	5.46	4.14	2.71	19.42	43.78	0.13
	5.80	4.18	2.71	19.32	43.91	0.14
	6.13	4.31	2.74	19.70	45.77	0.16
	6.44	4.18	2.68	19.14	44.01	0.15
	8.76	4.29	2.85	21.44	47.34	0.10
	9.09	4.34	2.51	19.81	46.33	0.17
	9.41	4.24	2.78	20.35	45.61	0.12

Table 6: Summary of Uniaxial Compression Properties: 33mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)												Poisson's Ratio
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	60 MPa	10%	20%	30%	40%	50%	75%	
209-018-EXT3 8.74	195	31.30	44.90	54.81	61.28	65.54	68.10	44.13	60.64	67.75	69.22	69.12	70.72	0.42
8.81	185	40.66	51.36	58.79	63.94	67.44	69.62	49.95	62.56	68.77	70.72	70.44	68.12	0.46
8.89	186	26.12	38.30	47.37	53.35	57.42	60.04	36.59	51.86	59.07	61.72	62.31	63.26	0.48
8.97	190	41.65	52.52	60.48	65.94	69.63	71.88	51.49	64.97	71.32	73.03	71.56	69.79	0.41
9.04	196	41.65	51.59	58.81	63.76	67.06	69.00	51.23	63.42	68.83	69.48	67.80	62.64	0.41
11.19	202	38.97	49.62	57.70	63.18	66.84	69.05	49.72	63.27	69.10	69.72	68.62	67.39	0.44
11.33	199	37.10	48.23	56.43	62.05	65.90	68.35	48.16	61.98	68.31	69.72	68.89	66.86	0.36
11.41	204	43.77	53.97	61.20	66.24	69.66	71.76	54.29	66.55	71.92	72.39	70.80	66.08	0.39
11.62	184	42.16	52.78	60.48	65.60	68.83	70.52	51.11	64.09	69.84	70.60	69.18	66.40	0.47
11.69	200	41.20	51.94	59.73	65.07	68.75	70.82	51.92	65.06	70.81	71.50	70.28	67.13	0.29
11.86	201	31.72	43.11	51.12	56.70	60.66	63.37	44.76	58.25	64.37	65.93	65.96	62.77	0.43
11.93	202	41.94	53.40	62.27	68.27	72.26	74.64	53.61	68.46	74.74	75.30	74.66	77.13	0.55
12.02	194	36.97	48.54	56.76	62.29	65.96	68.16	47.92	61.73	67.86	68.99	68.23	63.44	0.37

Table 7: Summary of Uniaxial Compression Properties: 45mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)												Poisson's Ratio
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	60 MPa	10%	20%	30%	40%	50%	75%	
209-025-SV2 6.15	180	41.13	50.87	57.59	62.16	65.14	66.80	48.45	59.82	65.49	67.30	66.82	63.68	0.26
6.25	185	36.48	50.39	58.50	63.45	66.13	66.90	48.79	62.23	66.78	69.85	70.72	65.80	0.25
6.45	168	33.70	47.61	55.09	60.22	63.71	65.88	44.55	57.17	63.83	66.73	67.34	62.88	0.40
6.68	179	43.60	53.52	60.27	64.93	68.03	69.84	51.11	62.53	68.39	70.49	70.53	64.67	0.29
6.78	179	38.12	47.57	54.24	58.81	61.84	63.62	44.99	56.27	62.06	64.25	64.76	63.11	0.27
6.91	169	40.39	49.71	56.23	60.68	63.60	65.25	47.17	58.16	63.78	65.73	65.24	57.45	0.32
7.03	157	39.56	51.55	59.33	64.25	67.08	68.16	45.95	59.20	65.80	68.15	66.26	64.64	0.28
7.15	173	46.55	56.25	62.83	67.11	69.62	70.62	53.76	64.85	69.83	70.85	71.01	69.63	0.36
7.24	170	41.13	51.75	59.00	63.86	66.97	68.63	48.28	60.52	66.74	68.99	68.87	70.05	0.37
7.37	172	41.31	51.81	59.07	63.94	67.08	68.44	47.94	60.18	66.56	69.08	69.11	66.41	0.32
7.65	167	39.16	49.33	56.21	60.83	63.81	65.43	45.85	57.47	63.47	65.77	65.89	64.34	0.32
7.75	153	35.73	48.37	57.07	62.85	66.63	68.83	42.62	57.45	65.26	68.99	69.76	68.42	0.24

Table 8: Summary of Uniaxial Compression Properties: 63mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)												Poisson's Ratio
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	60 MPa	10%	20%	30%	40%	50%	75%	
209-017-SMF1 1.33	193	35.95	46.45	53.00	57.81	61.37	63.94	45.91	57.23	63.48	66.44	67.46	65.30	0.32
1.75	198	28.83	39.95	47.74	53.10	56.86	59.39	39.79	52.94	59.28	61.45	61.48	57.33	0.25
1.89	198	32.70	43.46	50.72	55.83	59.47	61.95	43.31	55.69	61.85	64.08	64.36	59.51	0.40
2.45	192	33.41	44.17	51.46	56.63	60.32	62.87	43.36	55.82	62.28	65.02	65.26	61.32	0.34
2.59	192	31.87	43.56	51.75	57.41	61.39	64.07	42.79	55.67	63.56	66.17	66.52	63.01	0.24
2.87	190	32.66	43.80	51.57	57.06	61.00	63.76	42.87	56.13	63.07	66.17	66.85	62.89	0.33
209-015-SMR1 0.93	201	29.31	41.80	50.23	55.92	59.80	62.30	41.94	56.05	62.38	63.91	63.50	59.95	0.31
2.18	221	34.15	45.66	53.52	58.99	62.83	65.30	47.60	60.79	66.45	67.43	67.04	62.27	0.26
2.33	217	31.72	43.11	51.12	56.70	60.66	63.37	44.76	58.25	64.37	65.93	65.96	62.77	0.43
2.60	192	30.16	42.99	51.85	57.93	62.21	65.11	42.15	57.14	64.56	67.50	68.15	67.64	0.29

Table 9: Summary of Uniaxial Compression Properties: 141mm Diameter Specimens

Specimen Identification	Uniaxial Compressive Strength (MPa)	Tangent Modulus of Elasticity (GPa)												Poisson's Ratio
		10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	60 MPa	10%	20%	30%	40%	50%	75%	
209-055-OC3 4.82	175	31.00	38.81	46.84	52.22	55.87	58.19	36.11	49.74	56.53	59.47	60.20	64.66	0.29
5.46	175	25.75	36.12	45.83	52.12	56.36	59.10	32.70	49.24	57.14	60.60	61.40	61.08	0.27
5.80	169	31.22	39.30	47.27	52.83	56.80	59.59	36.00	49.55	56.98	61.02	62.60	62.61	0.35
6.13	171	30.11	39.56	48.12	53.82	57.67	60.12	36.14	50.73	58.02	61.35	61.77	59.78	0.28
6.44	168	27.73	36.37	44.73	50.44	54.50	57.33	32.79	47.02	54.63	58.74	60.34	59.66	0.32
8.76	165	25.23	35.70	44.83	50.82	54.90	57.57	31.26	46.87	54.73	58.60	59.78	56.90	0.30
9.09	173	24.39	34.89	44.35	50.65	55.05	58.09	31.34	47.59	55.76	60.06	61.67	64.17	0.42
9.41	170	29.99	39.70	48.99	55.23	59.56	62.48	35.95	51.79	59.94	64.16	65.44	67.69	0.44

Table 10: Mean Ultrasonic Velocity Properties

Specimen Diameter (mm)	P-wave Velocity (km/sec)	S-wave Velocity (km/sec)	Dynamic Shear Modulus (GPa)	Dynamic Young's Modulus (GPa)	Poisson's Ratio
33	4.78 (0.10)	2.30 (0.07)	14.03 (0.81)	37.80 (1.77)	0.35 (0.02)
45	4.76 (0.15)	2.66 (0.10)	18.62 (1.32)	47.33 (2.82)	0.27 (0.03)
63	3.58 (0.11)	2.16 (0.06)	12.35 (0.66)	29.86 (1.32)	0.21 (0.03)
141	4.25 (0.11)	2.74 (0.11)	20.19 (1.12)	45.63 (2.22)	0.13 (0.02)

Table 11: Mean Uniaxial Mechanical Properties

	Stress Level (MPa)	Specimen Diameter			
		33 mm	45 mm	63 mm	141 mm
Uniaxial Compressive Strength (MPa)	0.10	195 (6.98)	171 (9.00)	199 (11.00)	171 (3.00)
Tangent Modulus of Elasticity (GPa)	10	38.09 (5.31)	39.74 (3.49)	32.08 (2.21)	28.18 (2.76)
	20	49.25 (4.64)	50.73 (2.51)	43.50 (1.82)	37.56 (1.97)
	30	57.38 (4.23)	57.95 (2.39)	51.30 (1.58)	46.37 (1.71)
	40	62.90 (4.05)	62.76 (2.32)	56.74 (1.60)	52.27 (1.67)
	50	66.61 (3.90)	65.80 (2.22)	60.59 (1.66)	56.34 (1.68)
	60	68.87 (3.74)	67.37 (2.07)	63.21 (1.72)	59.09 (1.69)
	10%	48.84 (4.76)	47.46 (3.01)	43.45 (2.19)	34.04 (2.22)
	20%	62.53 (4.12)	59.65 (2.57)	56.57 (2.03)	49.07 (1.78)
	30%	68.67 (3.80)	65.67 (2.19)	63.13 (1.91)	56.72 (1.76)
	40%	69.87 (3.33)	68.02 (2.07)	65.41 (1.85)	60.50 (1.79)
	50%	69.07 (2.91)	68.19 (2.17)	65.66 (2.04)	61.65 (1.80)
	75%	67.06 (3.98)	65.09 (3.42)	62.19 (2.93)	62.07 (3.42)
Poisson's Ratio	50%	0.42 (0.06)	0.31 (0.05)	0.32 (0.06)	0.33 (0.06)

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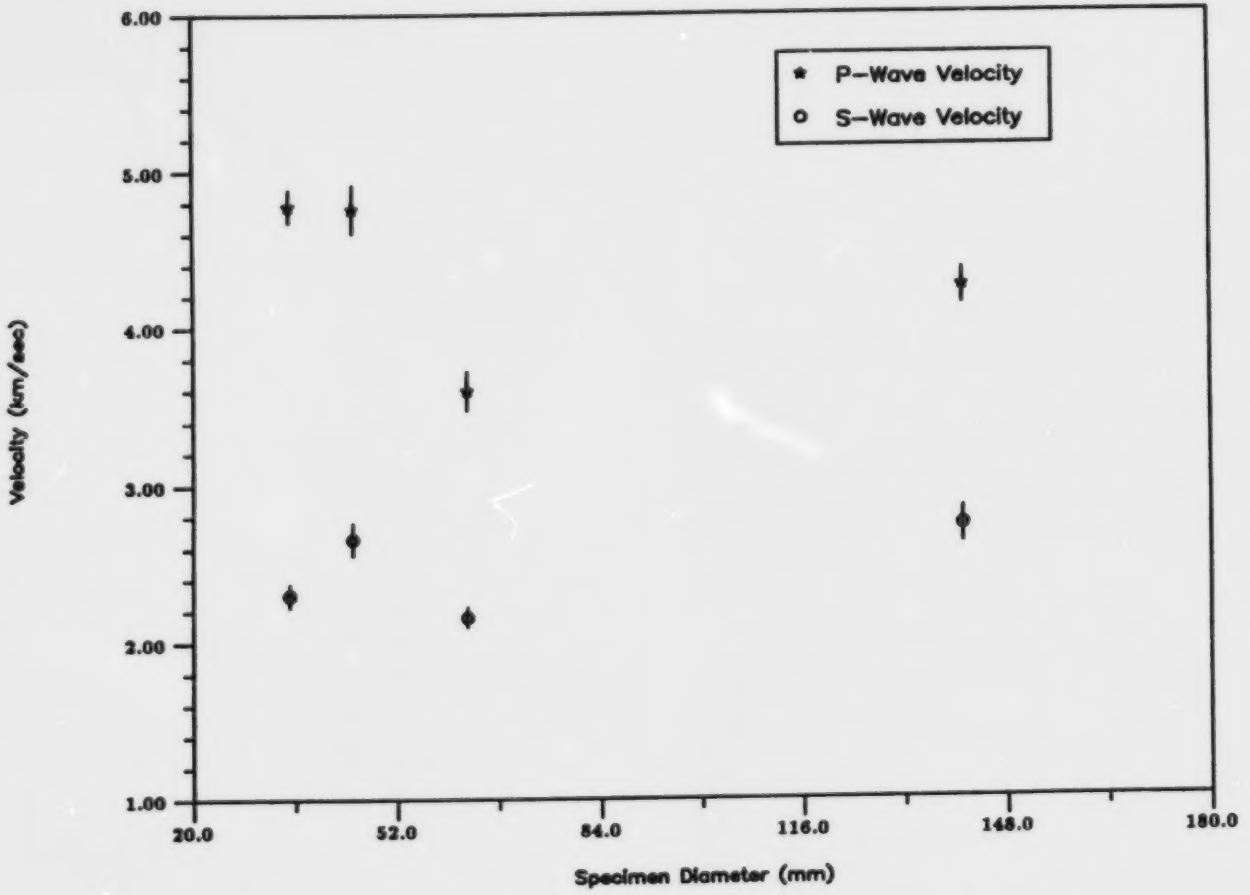

Figure 1: P and S Wave Velocities versus Specimen Diameter

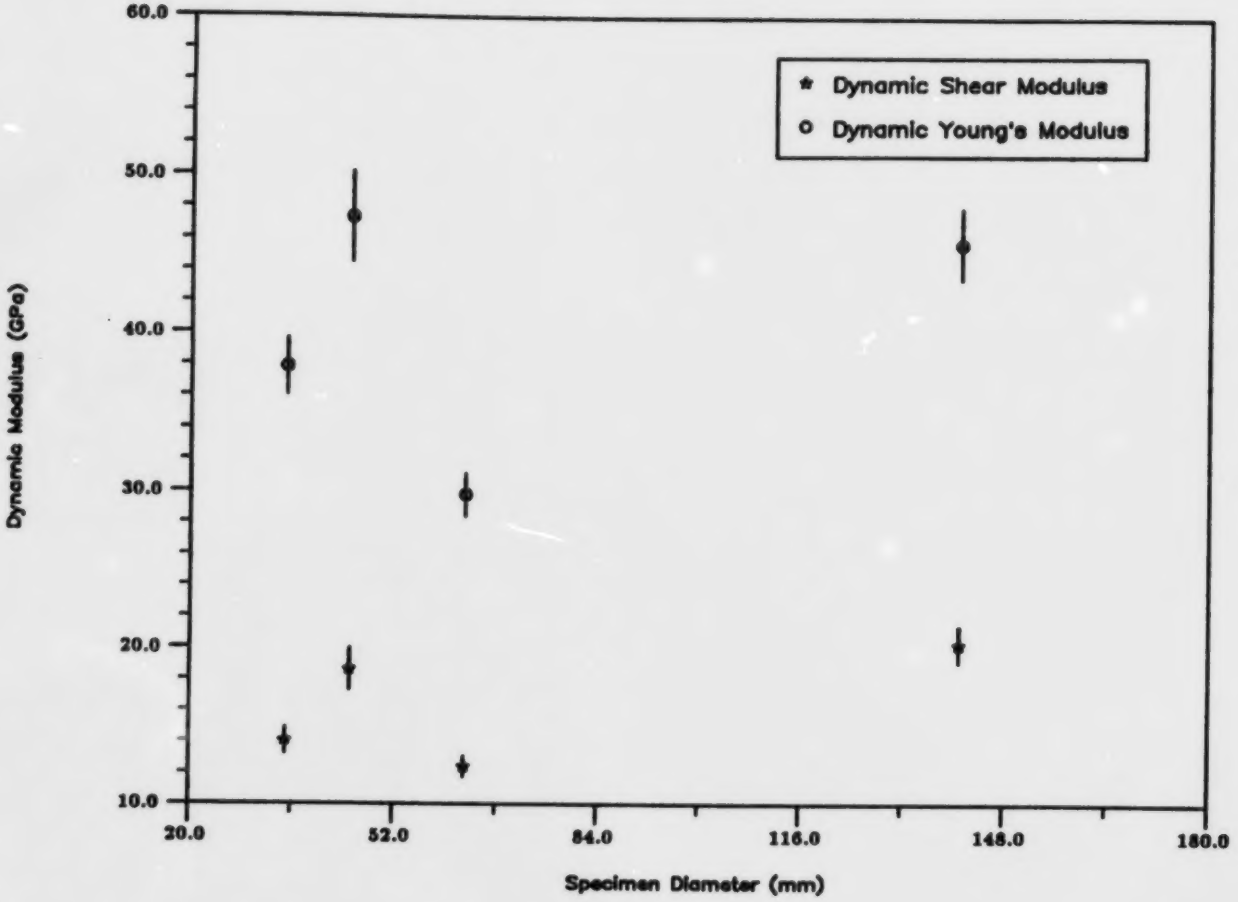

Figure 2: Dynamic Shear and Young's Moduli versus Specimen Diameter

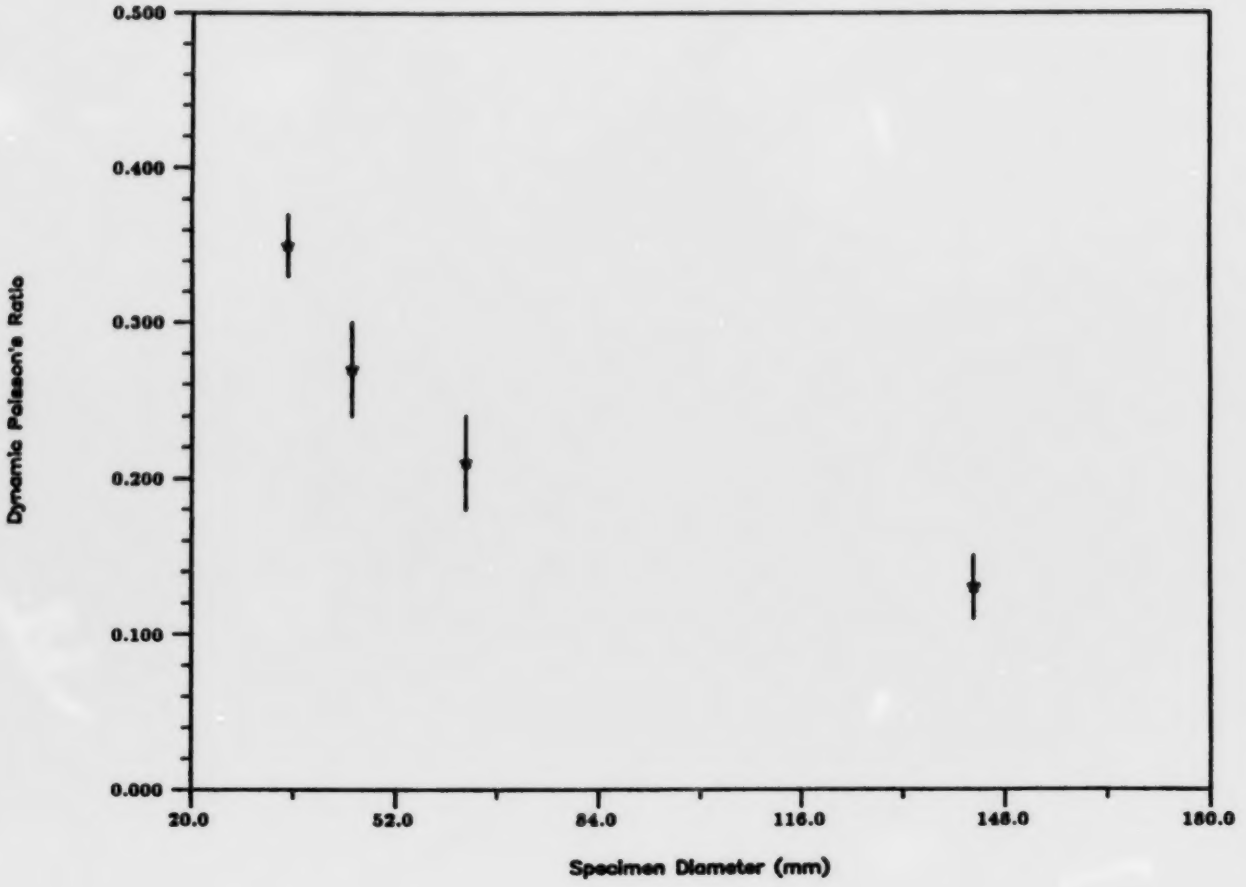

Figure 3: Dnamic Poisson's Ratio versus Specimen Diameter

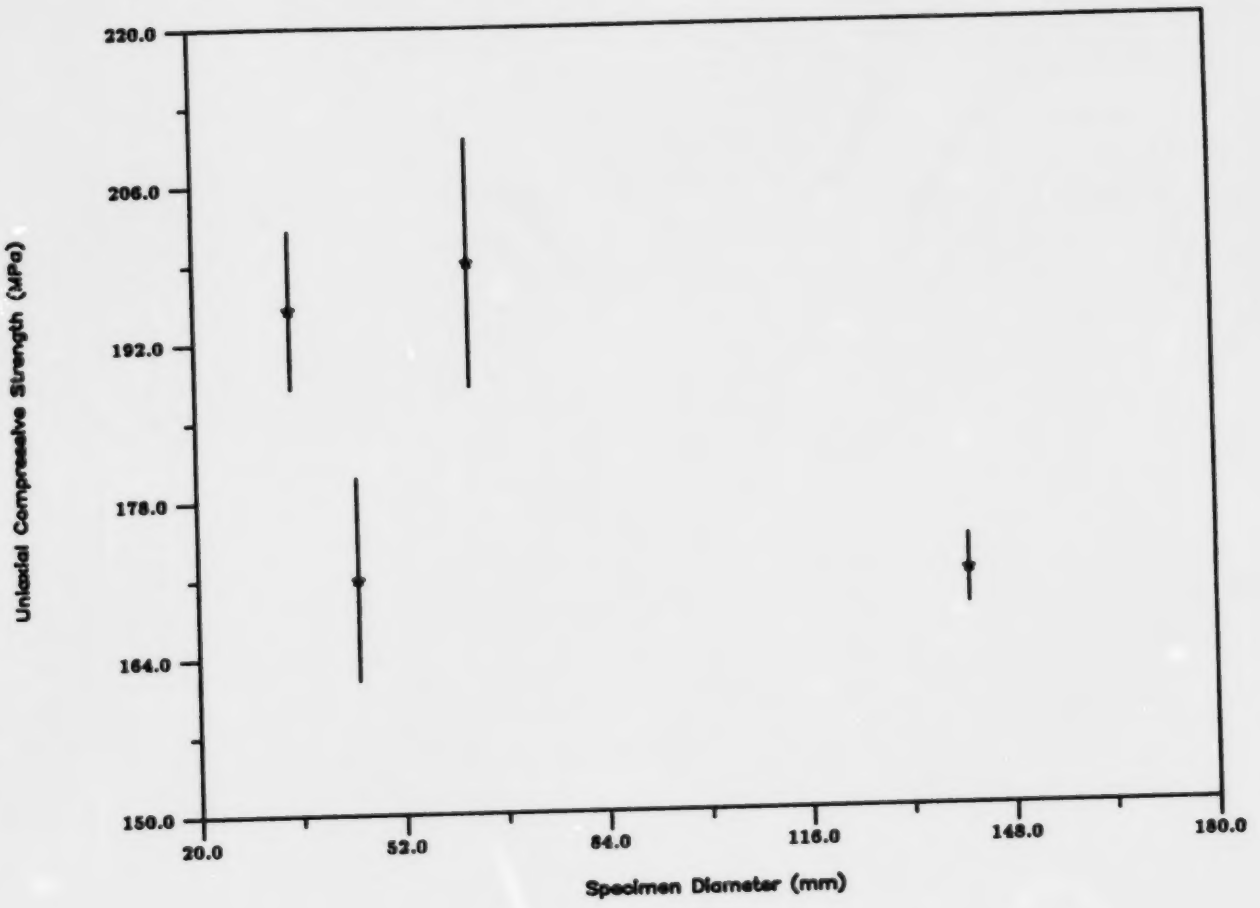

Figure 4: Uniaxial Compressive Strength versus Specimen Diameter

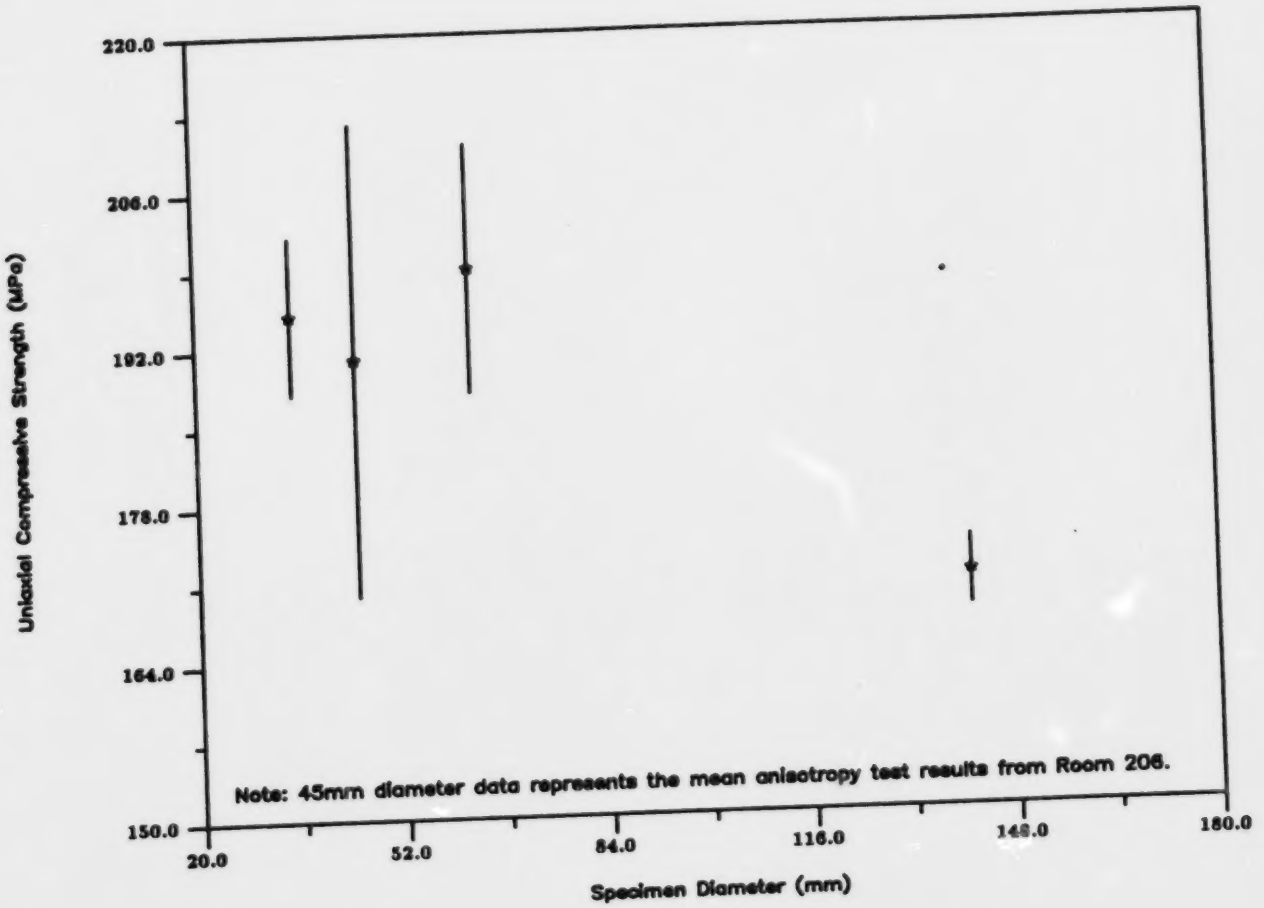

Figure 5: Uniaxial Compressive Strength versus Specimen Diameter: Room 206 Data

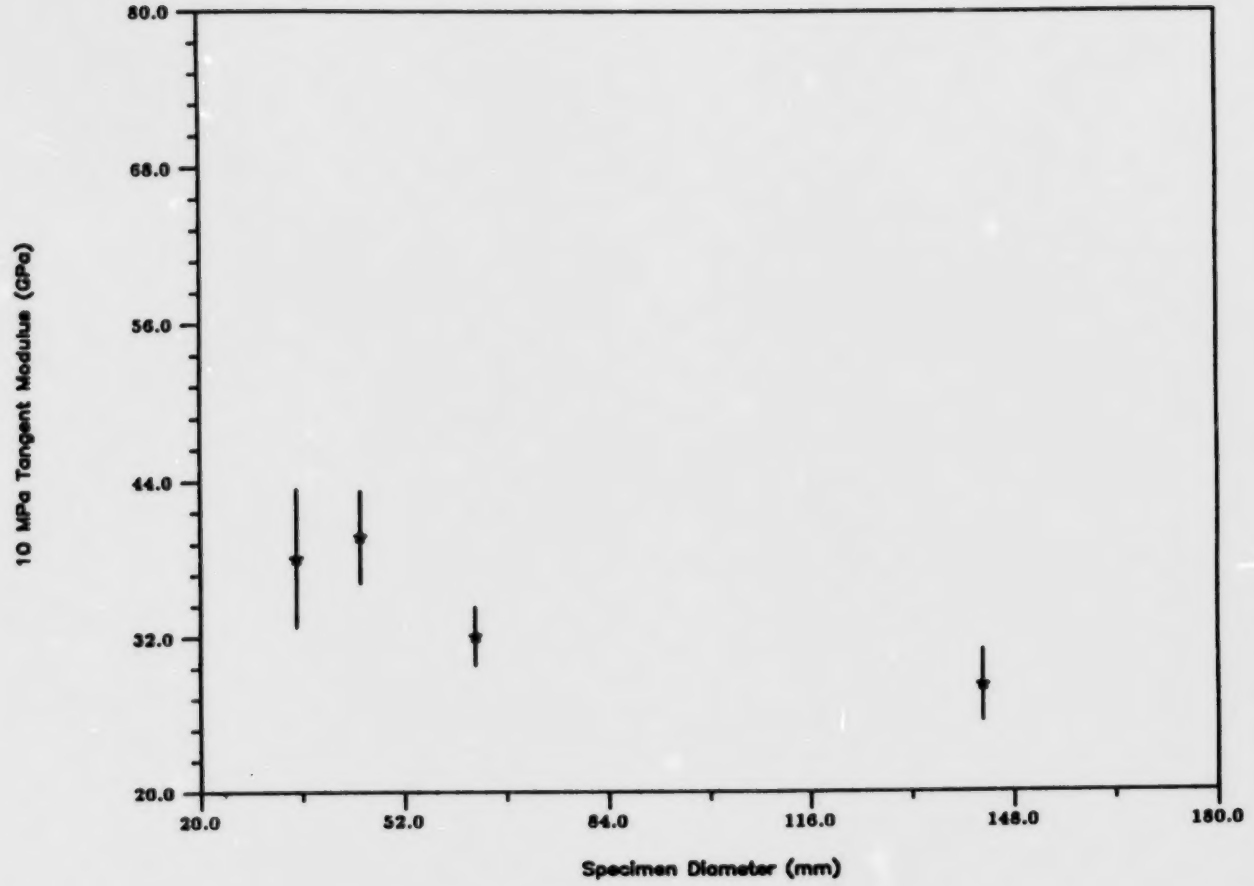

Figure 6: 10 MPa Tangent Modulus versus Specimen Diameter

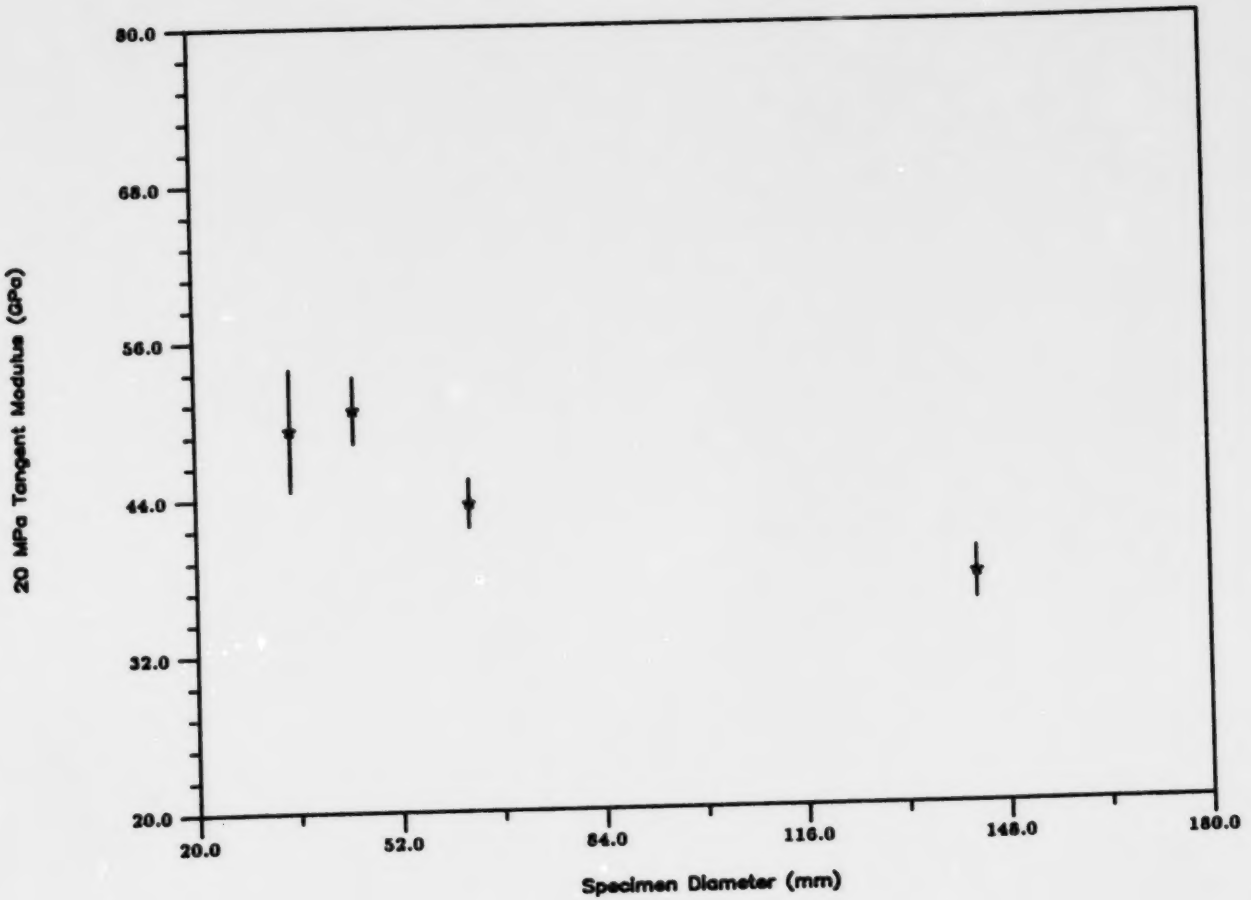

Figure 7: 20 MPa Tangent Modulus versus Specimen Diameter

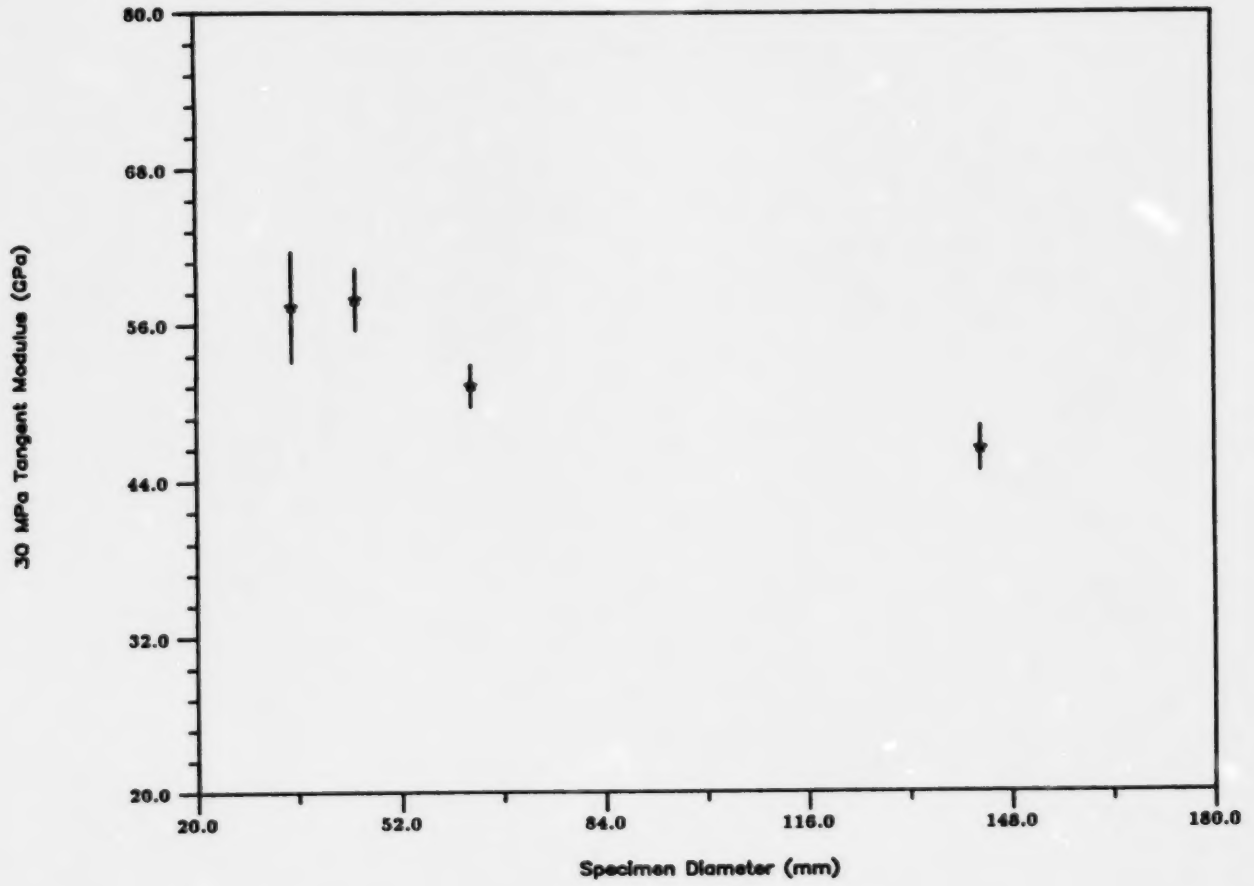

Figure 8: 30 MPa Tangent Modulus versus Specimen Diameter

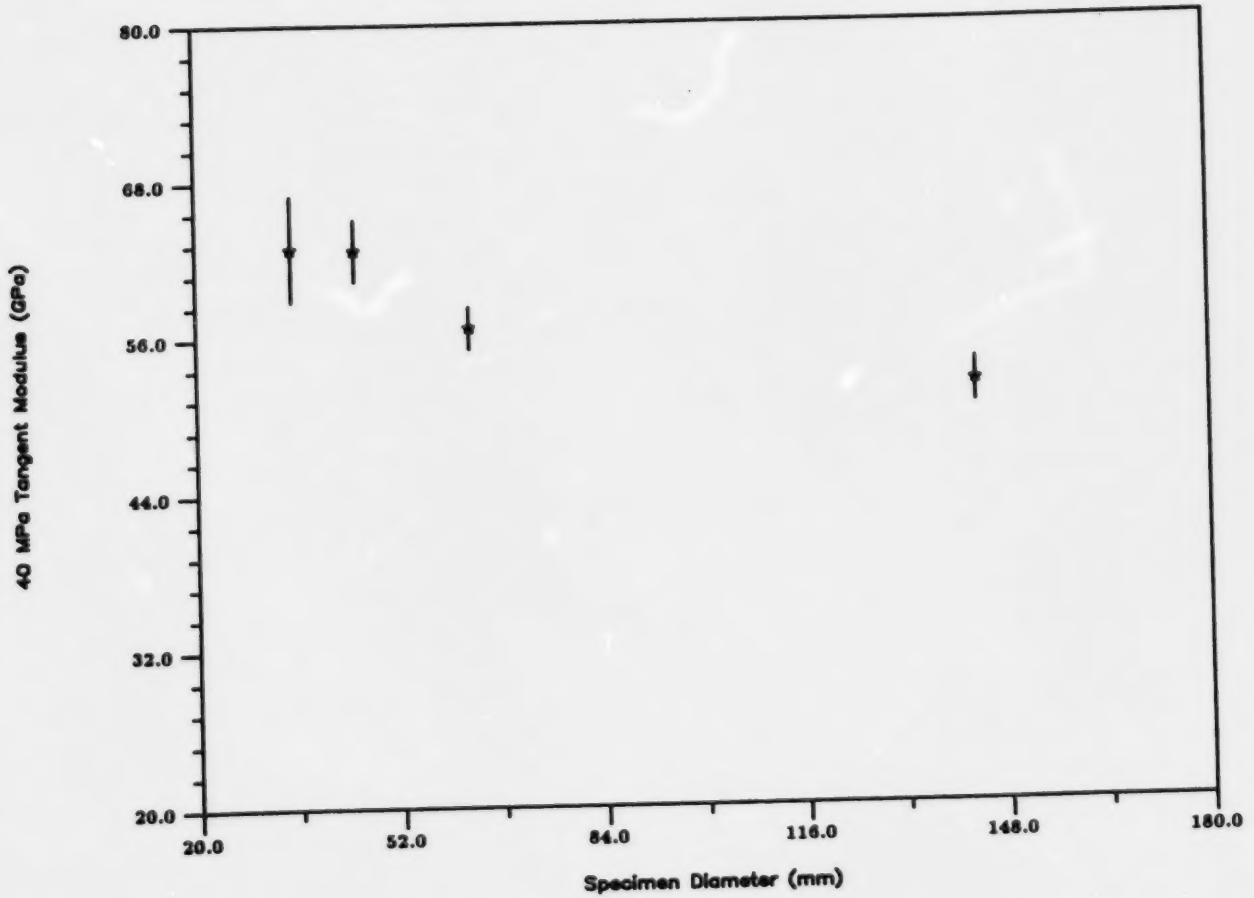

Figure 9: 40 MPa Tangent Modulus versus Specimen Diameter

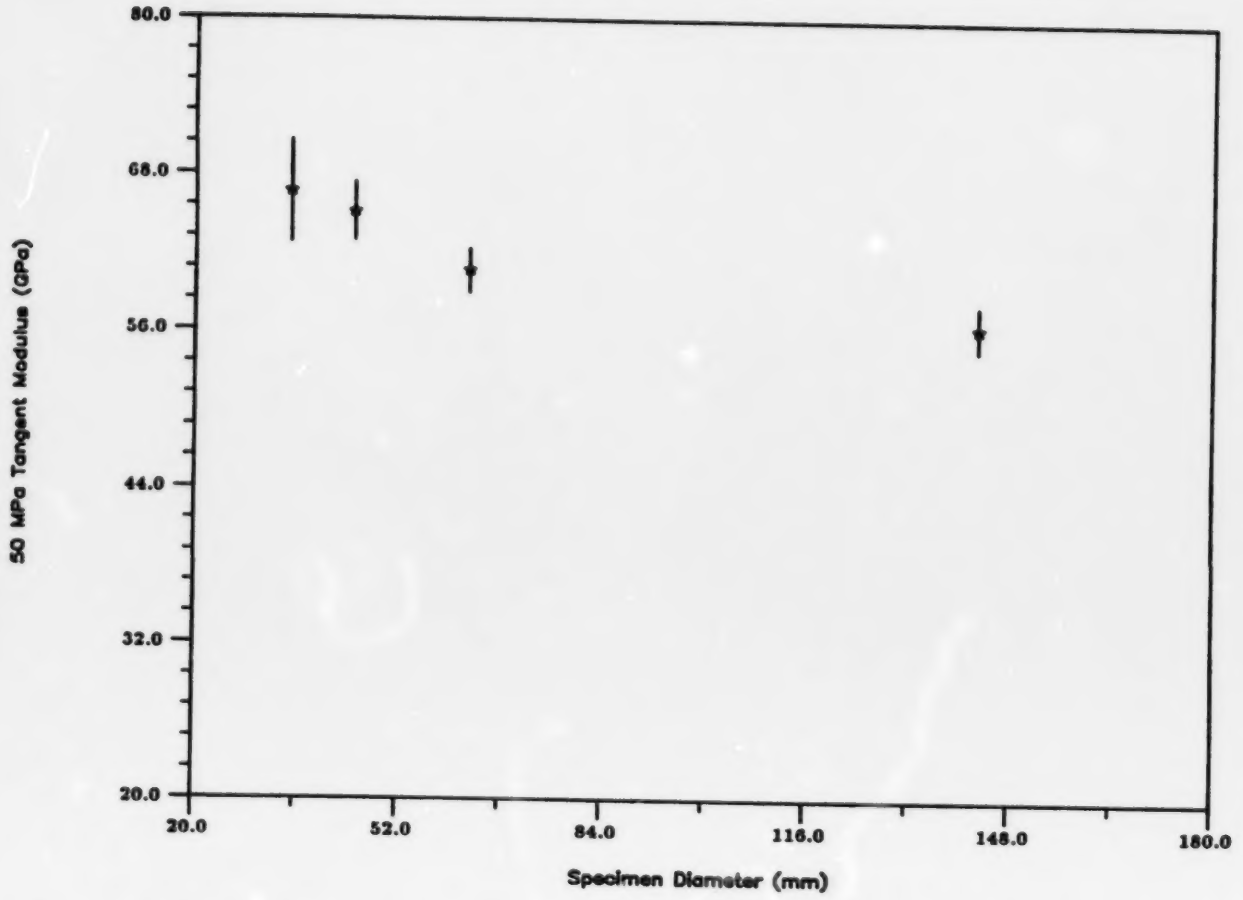

Figure 10: 50 MPa Tangent Modulus versus Specimen Diameter

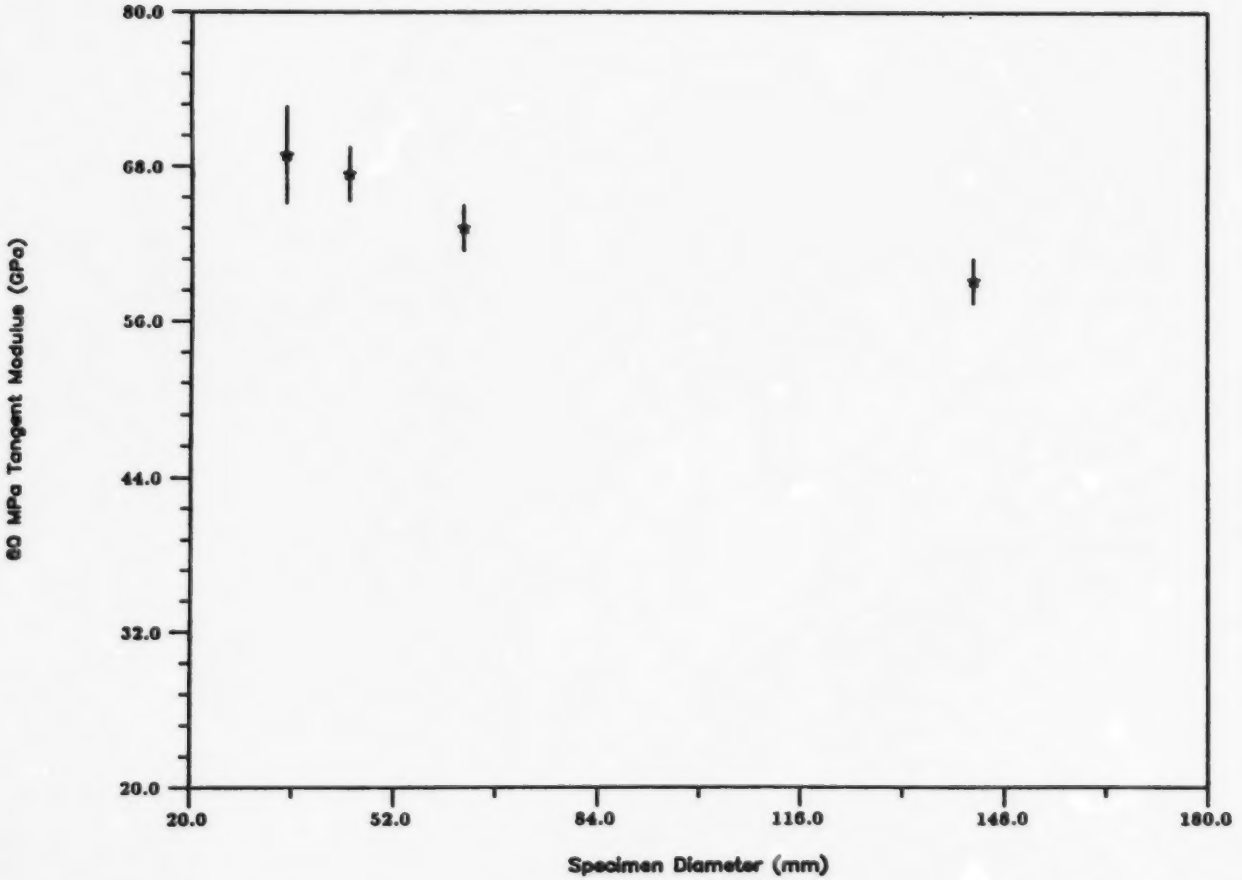

Figure 11: 60 MPa Tangent Modulus versus Specimen Diameter

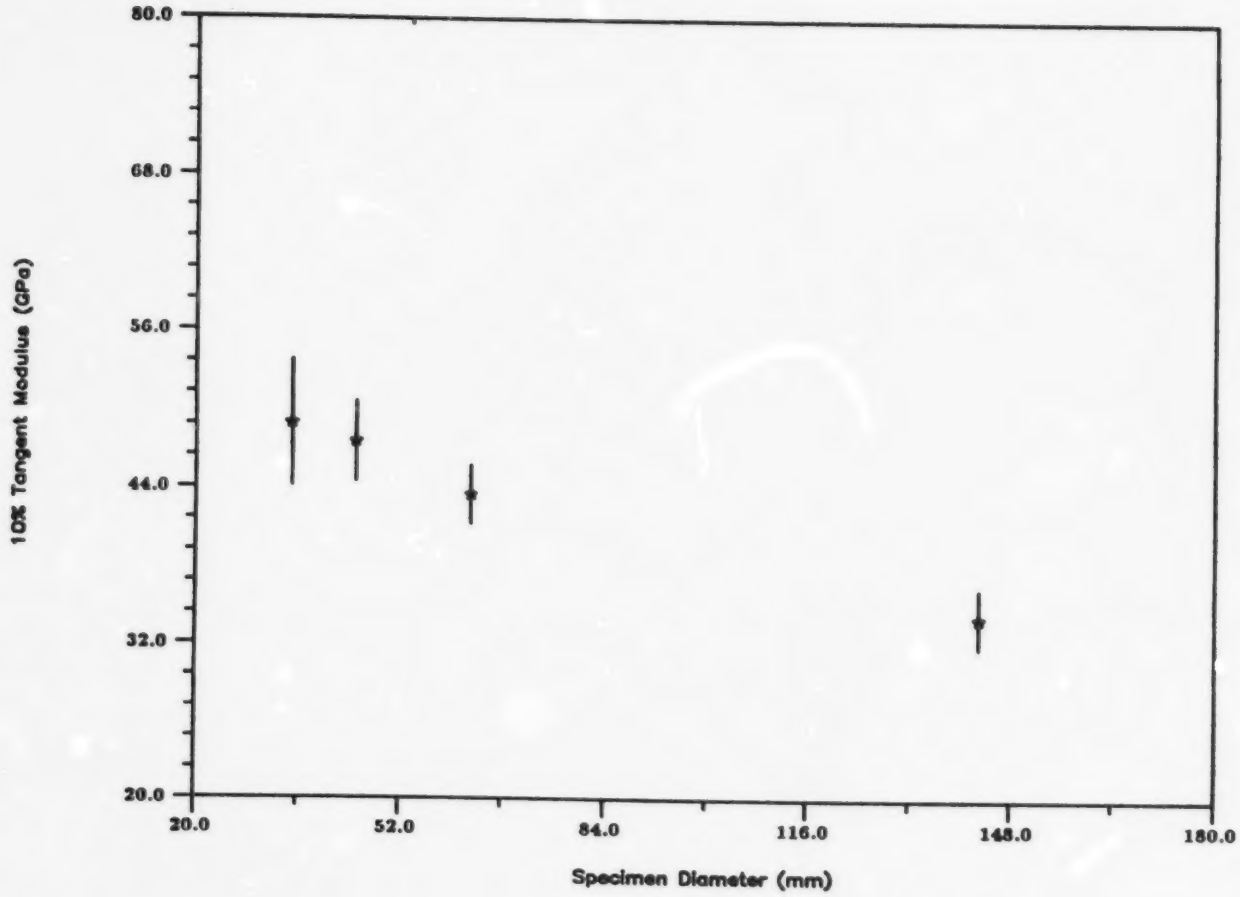

Figure 12: 10% Tangent Modulus versus Specimen Diameter

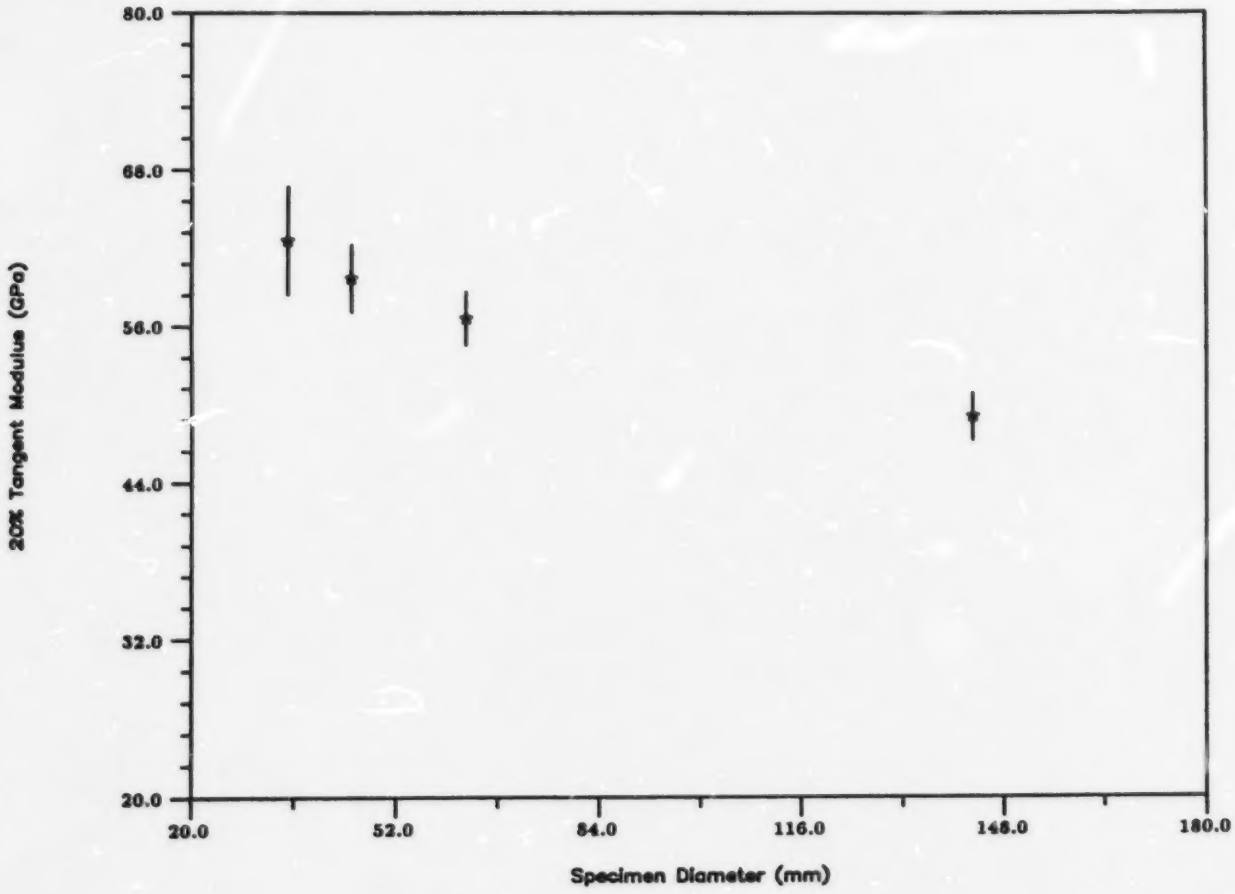

Figure 13: 20% Tangent Modulus versus Specimen Diameter

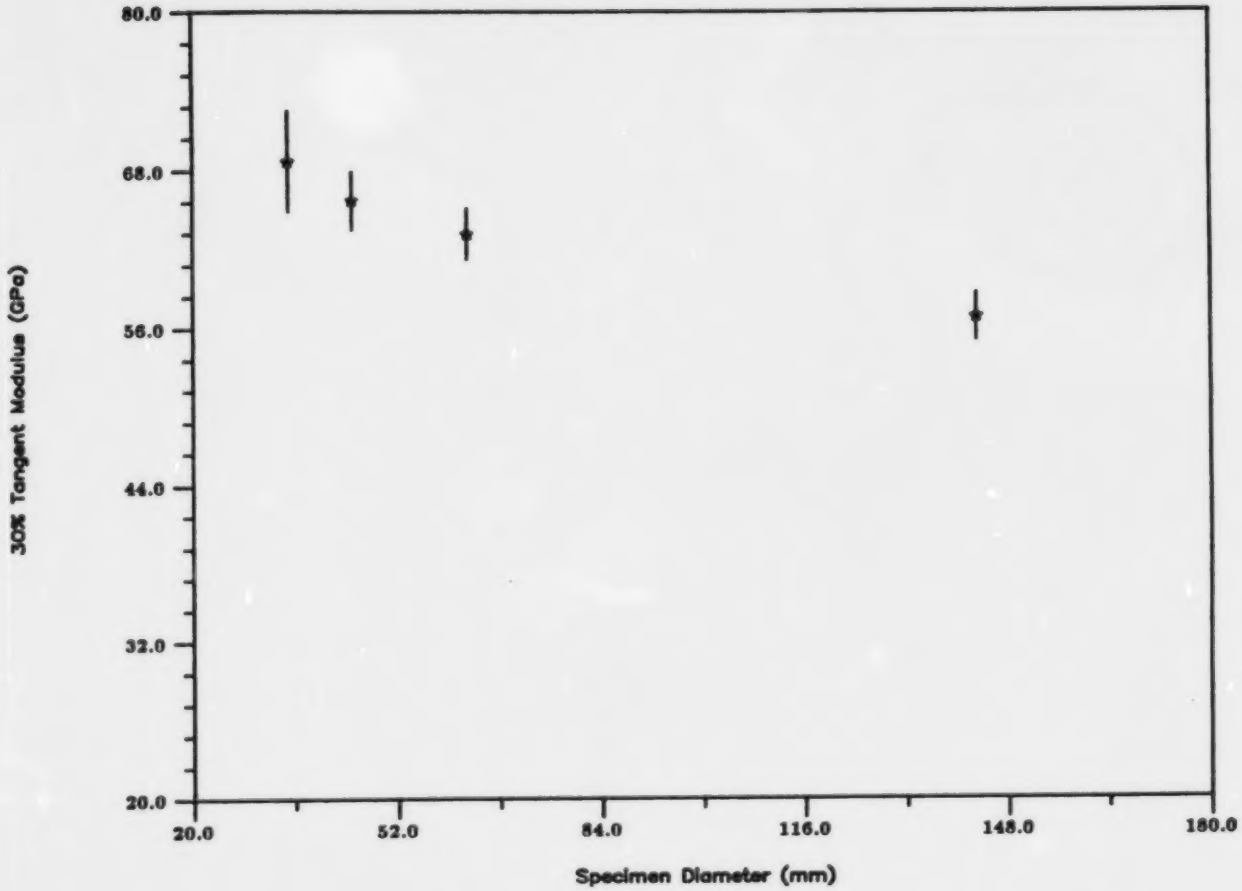

Figure 14: 30% Tangent Modulus versus Specimen Diameter

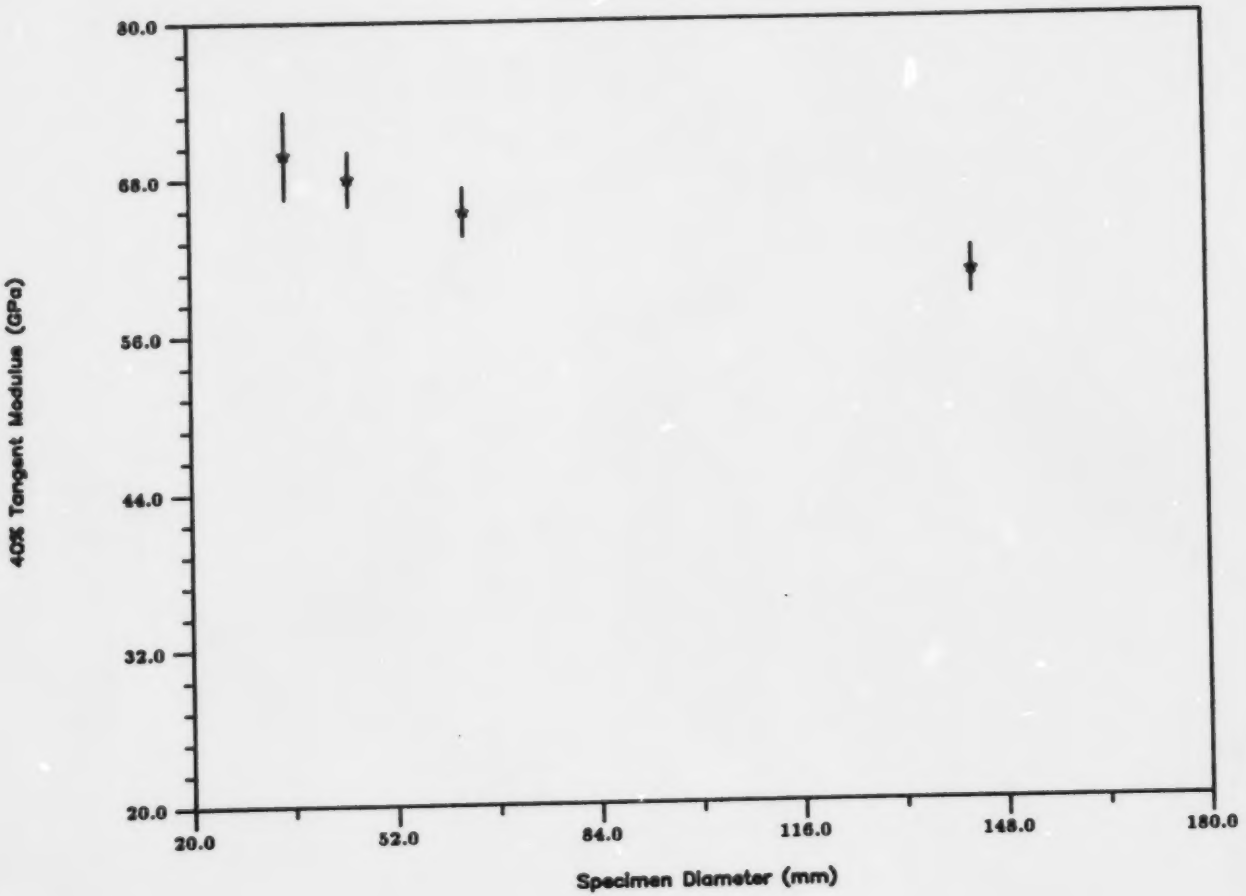

Figure 15: 40% Tangent Modulus versus Specimen Diameter

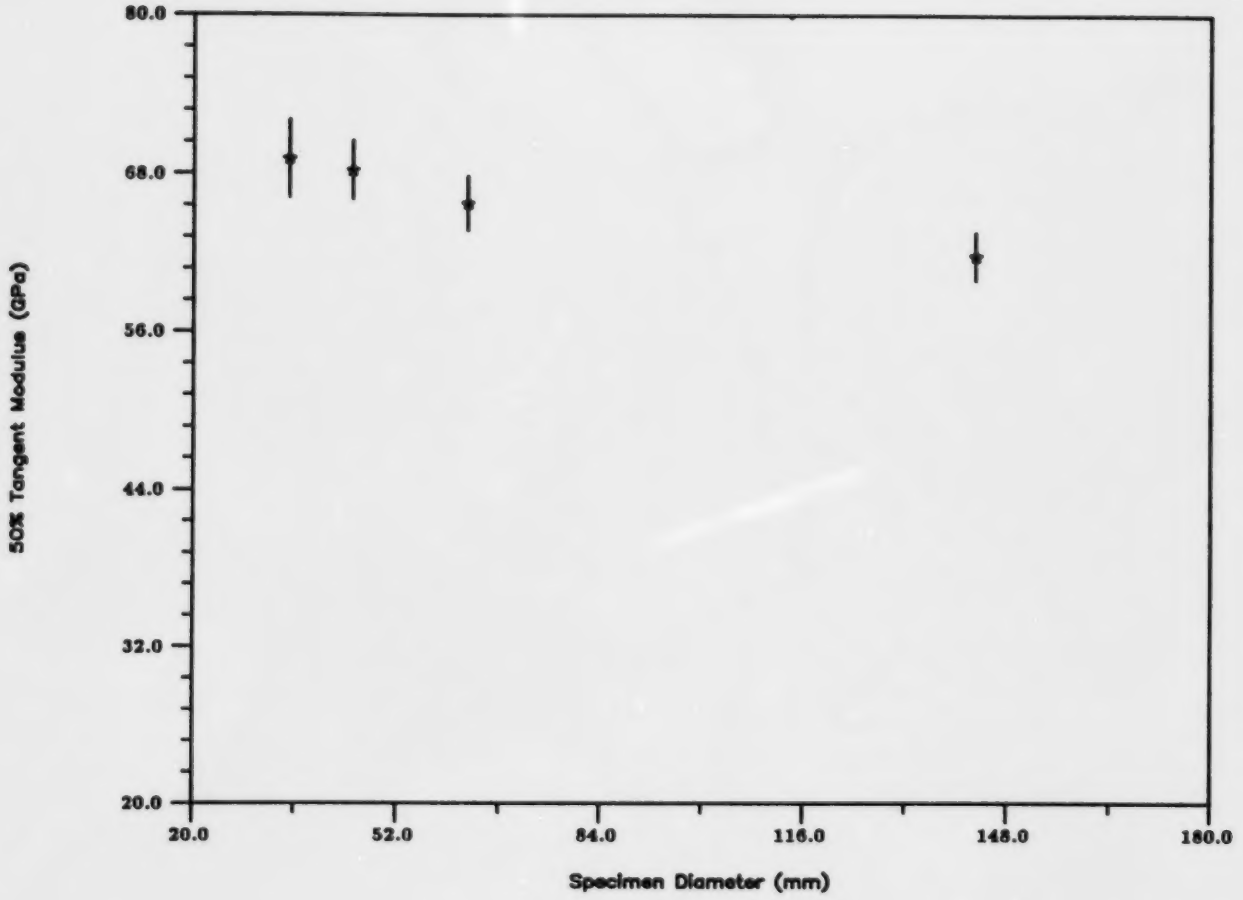

Figure 16: 50% Tangent Modulus versus Specimen Diameter

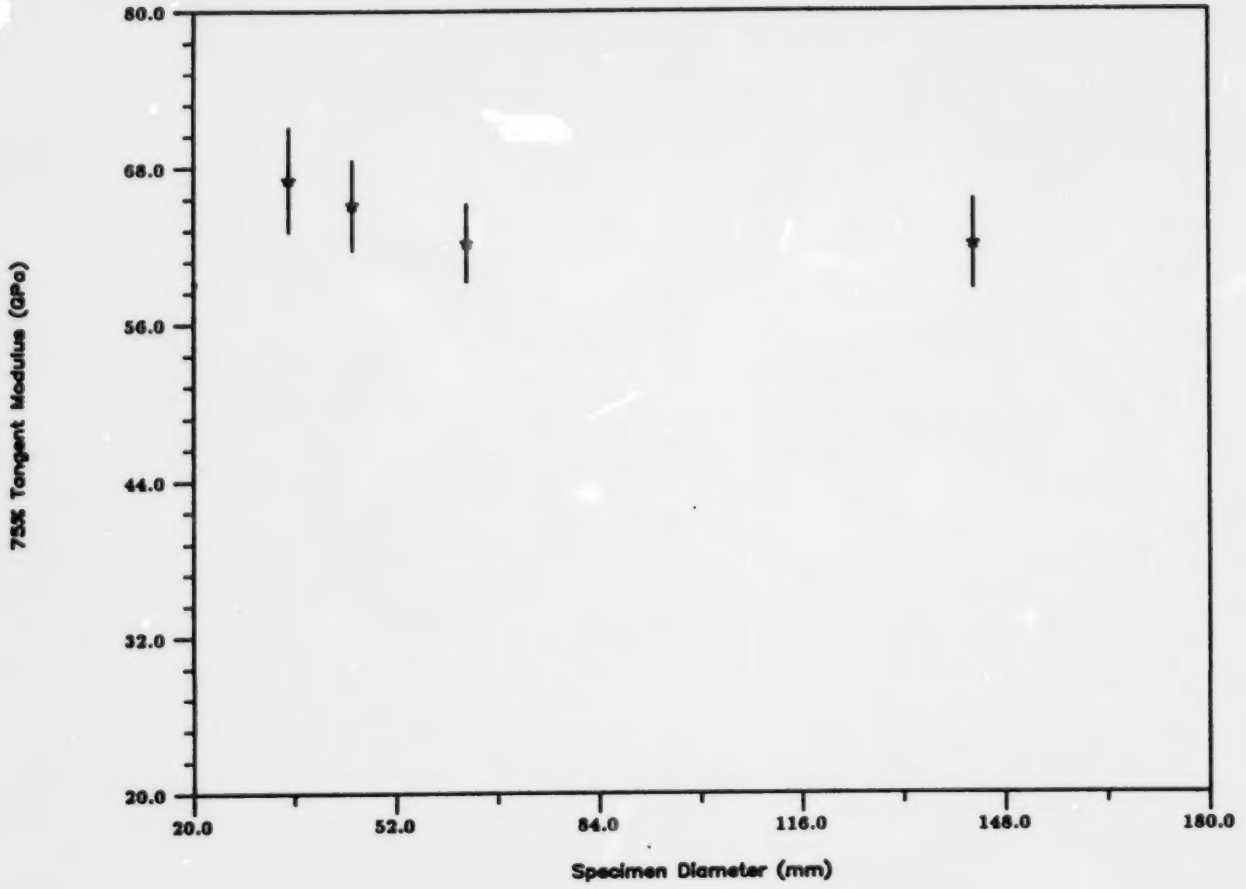

Figure 17: 75% Tangent Modulus versus Specimen Diameter

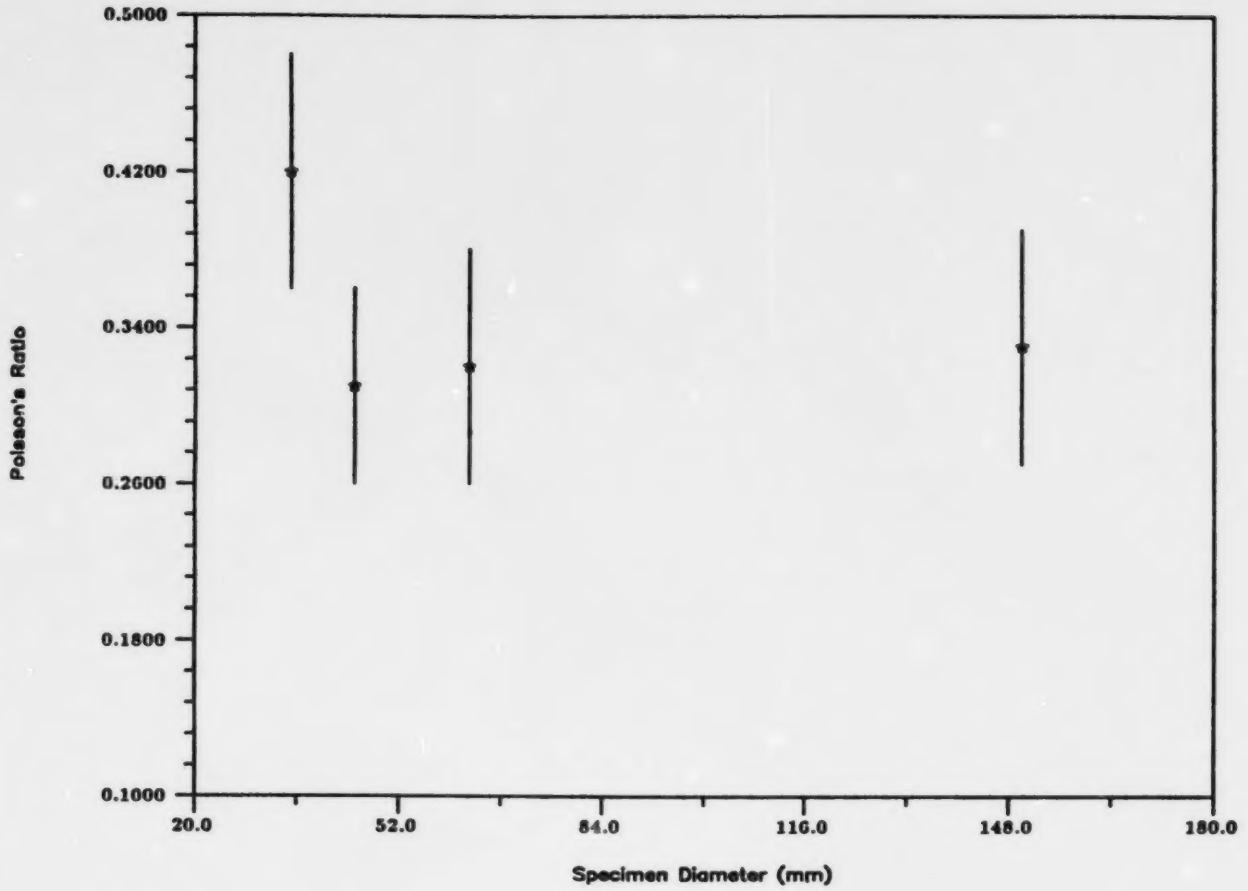

Figure 18: Poisson's Ratio versus Specimen Diameter

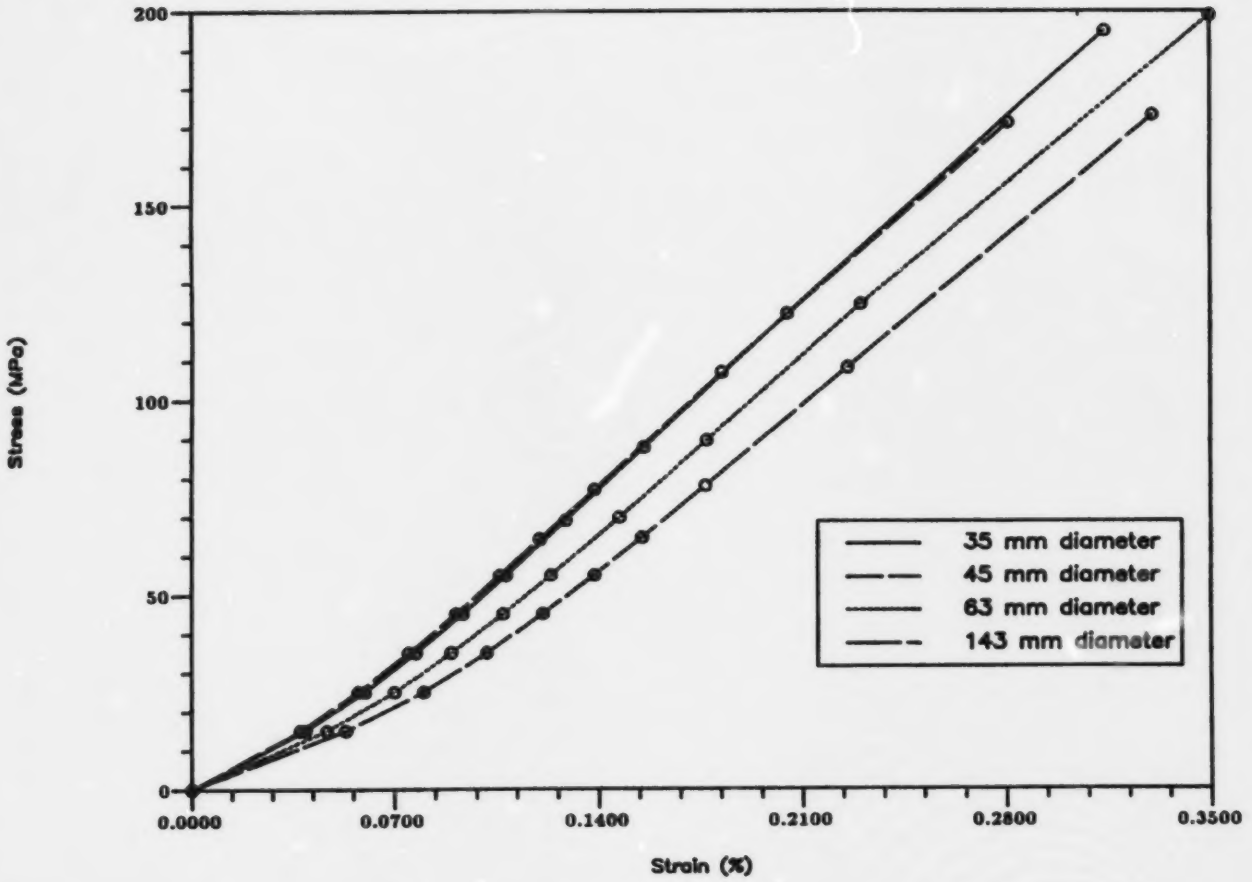

Figure 19: Pseudo-Stress/Strain Curves

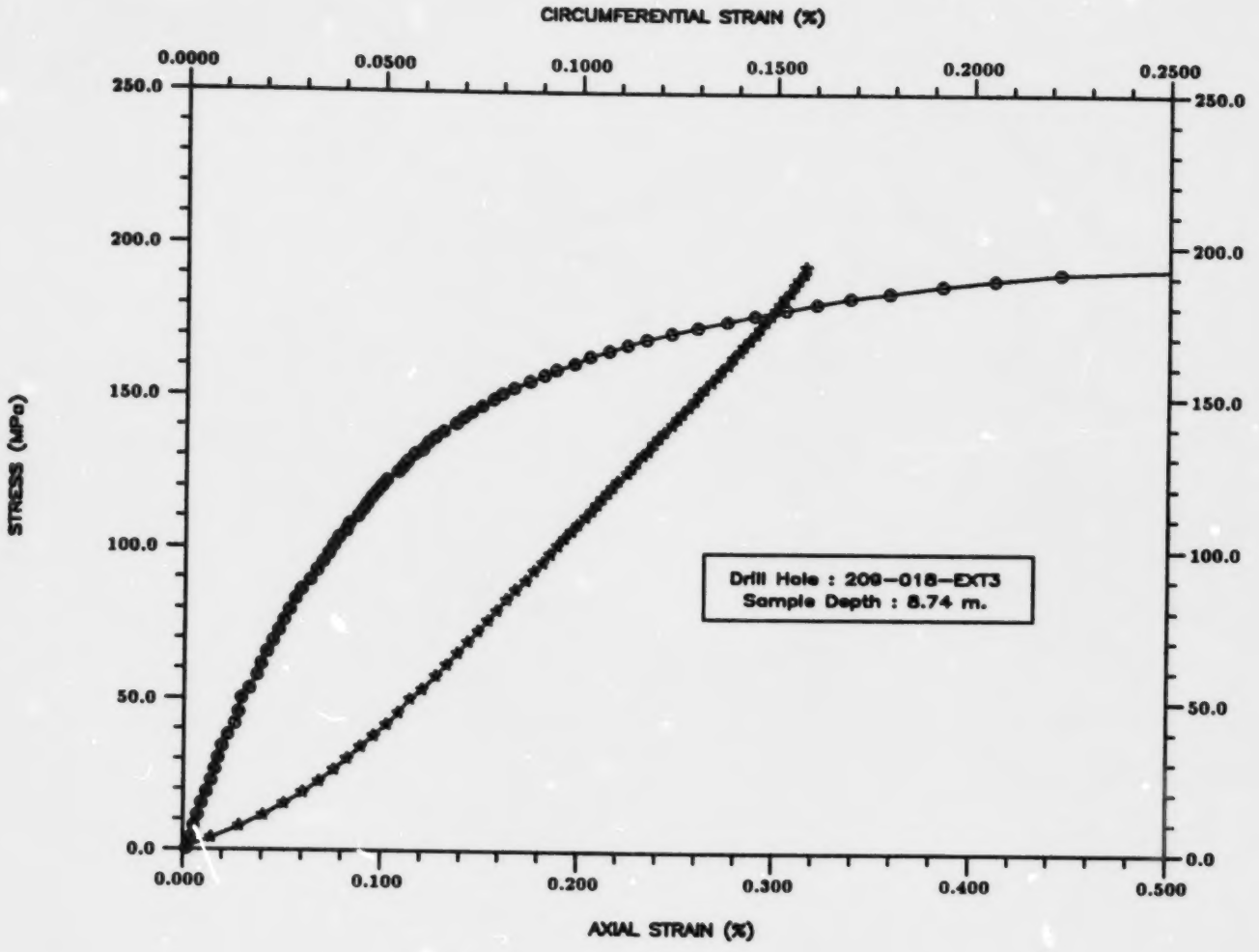

Figure 20: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

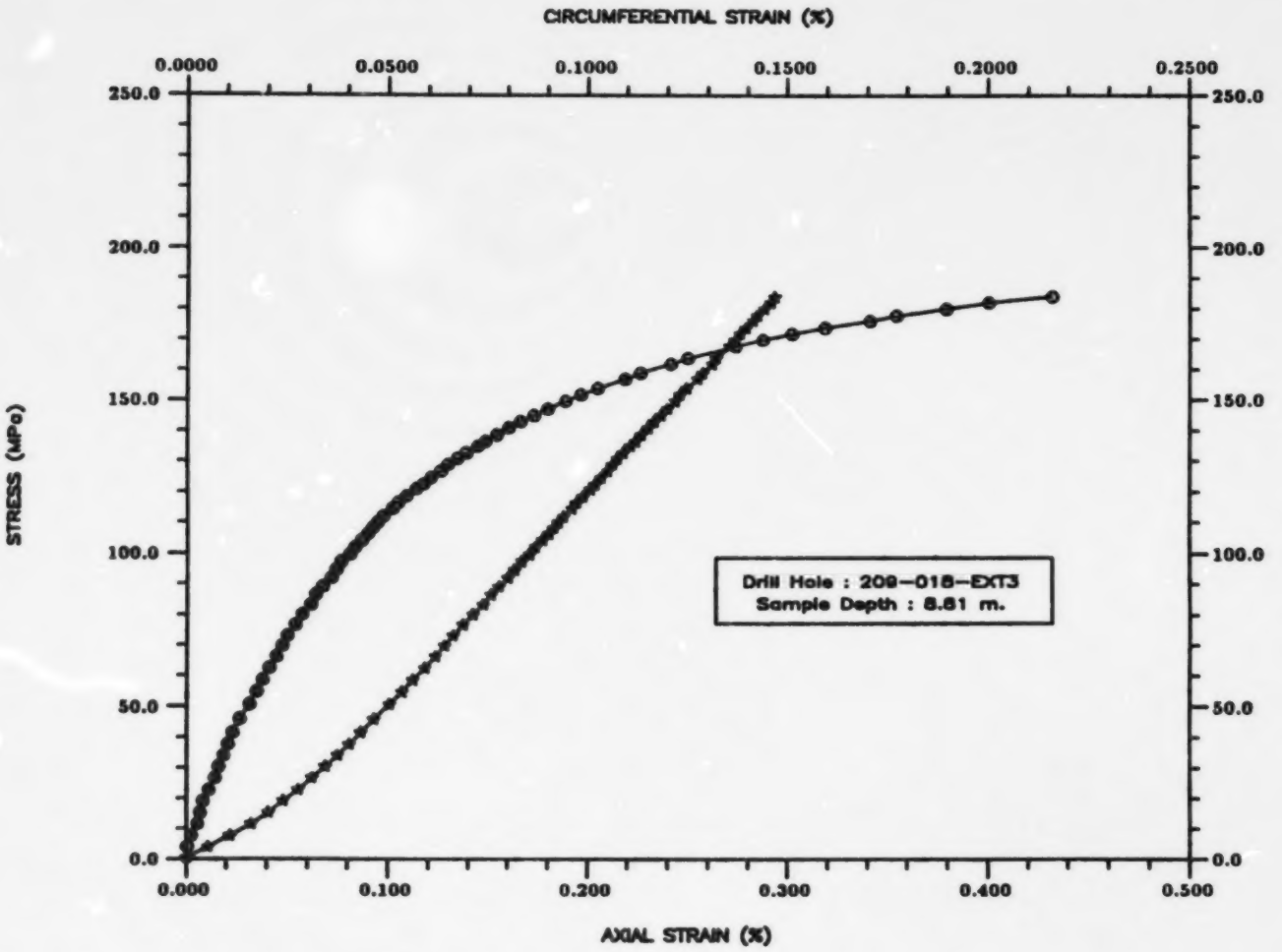

Figure 21: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

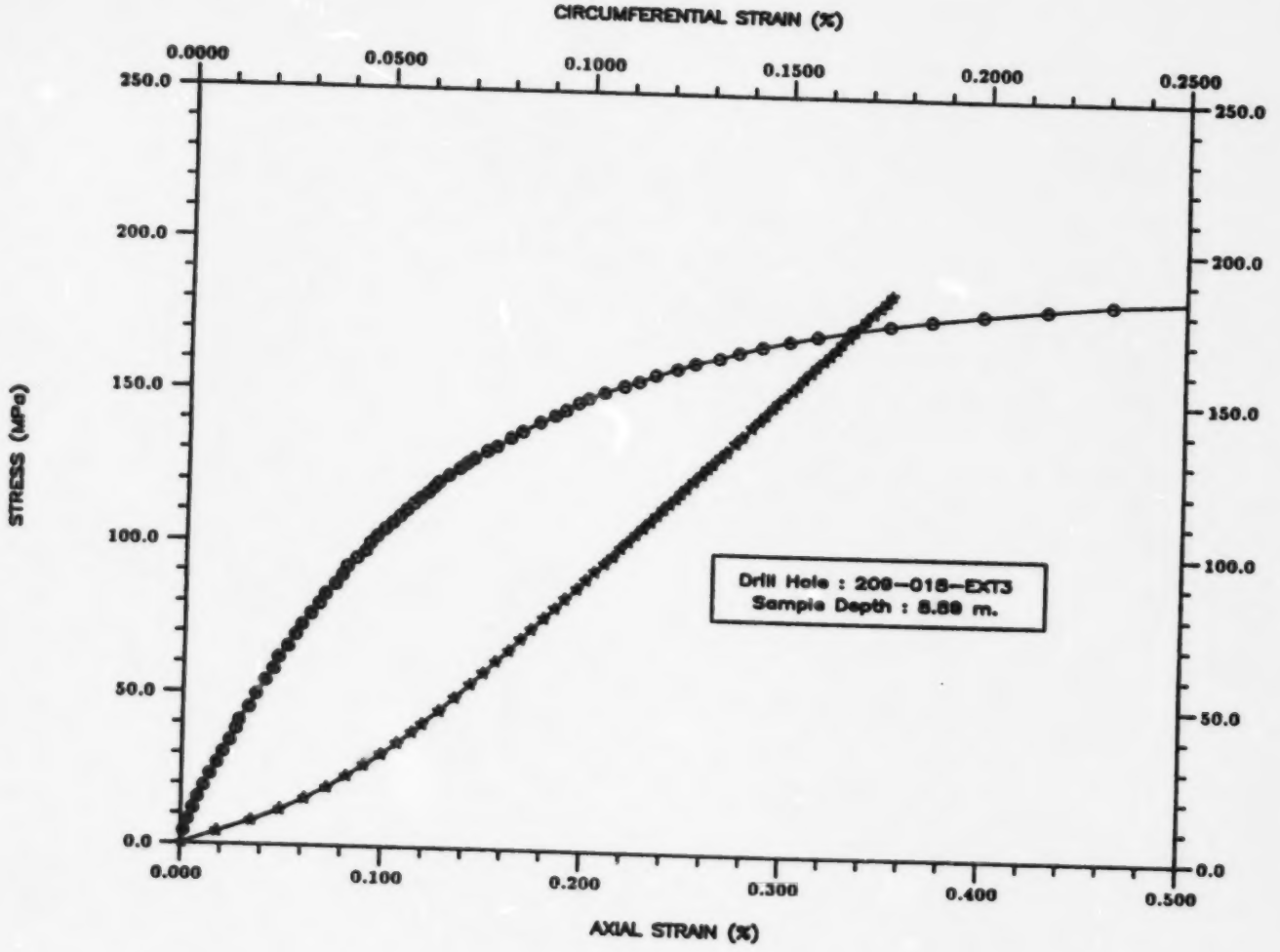

Figure 22: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

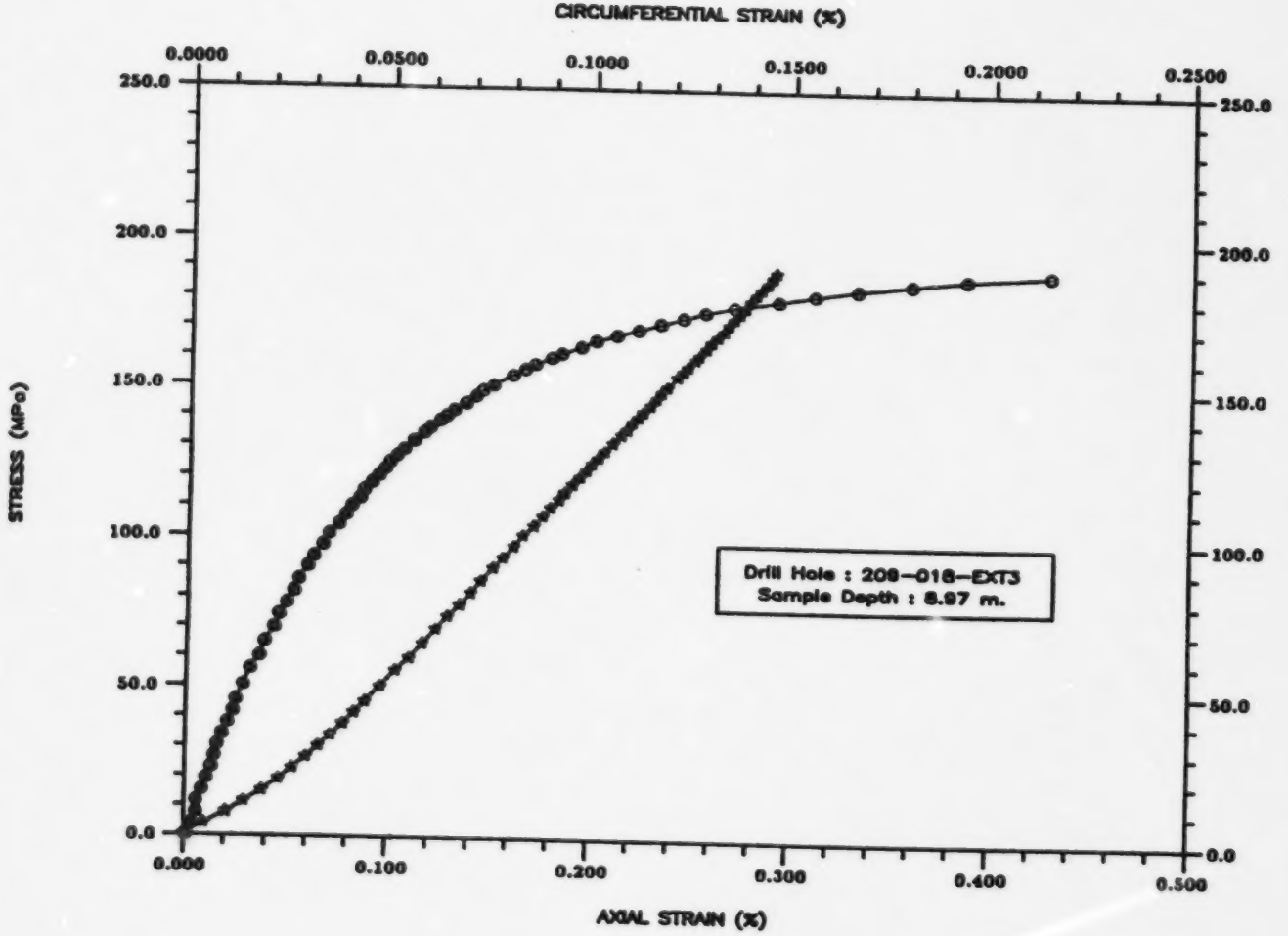

Figure 23: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

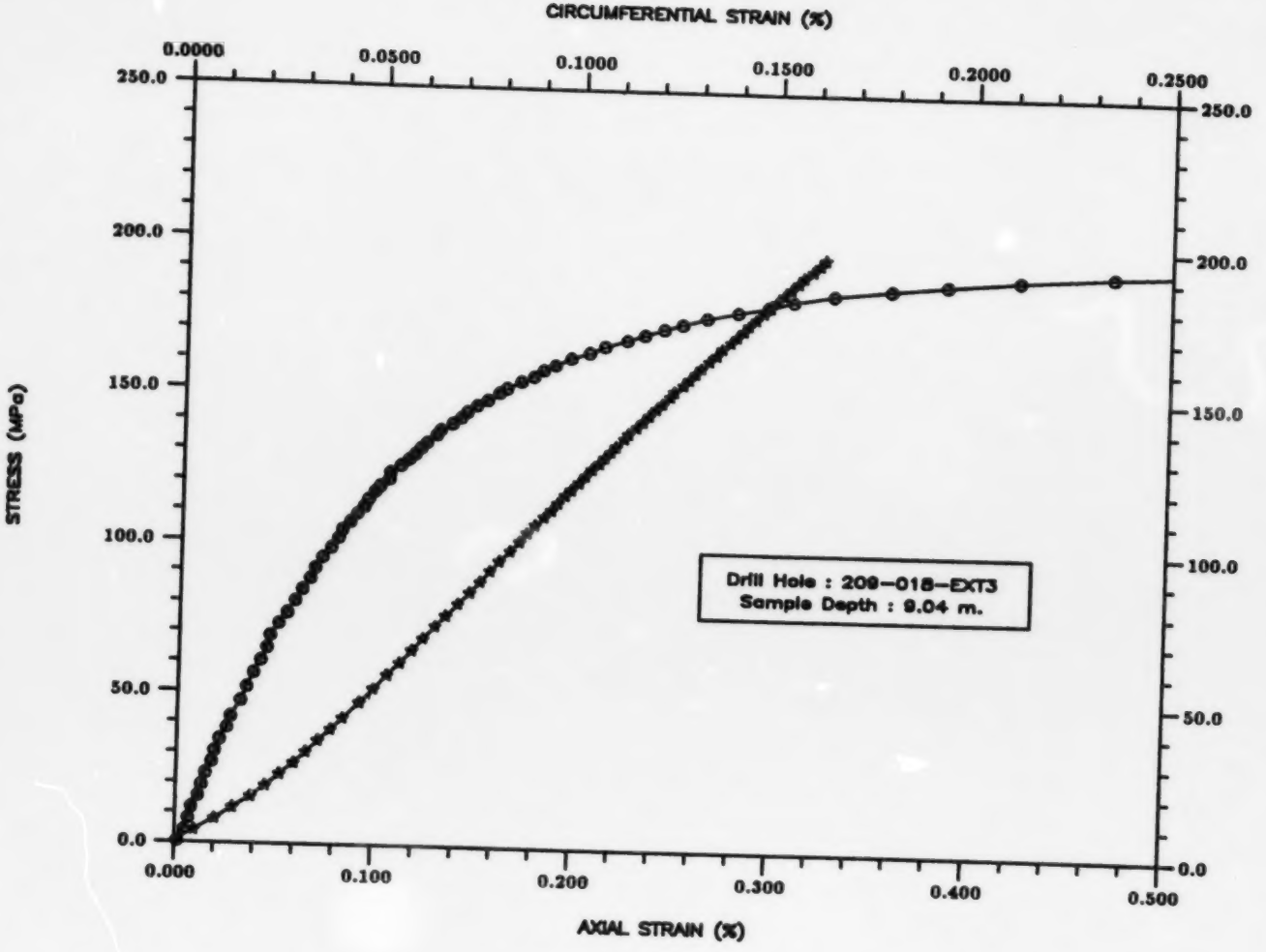

Figure 24: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

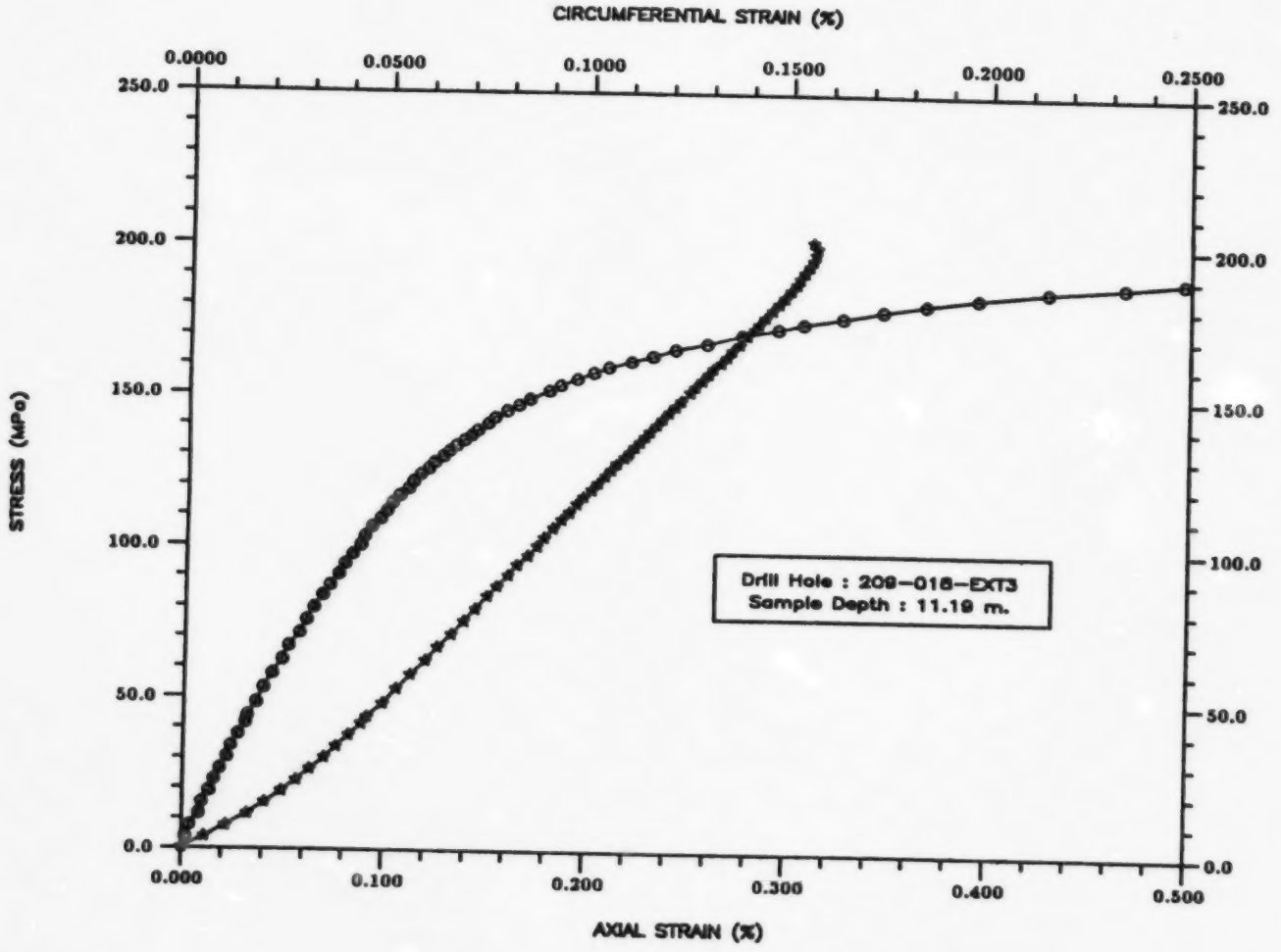

Figure 25: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

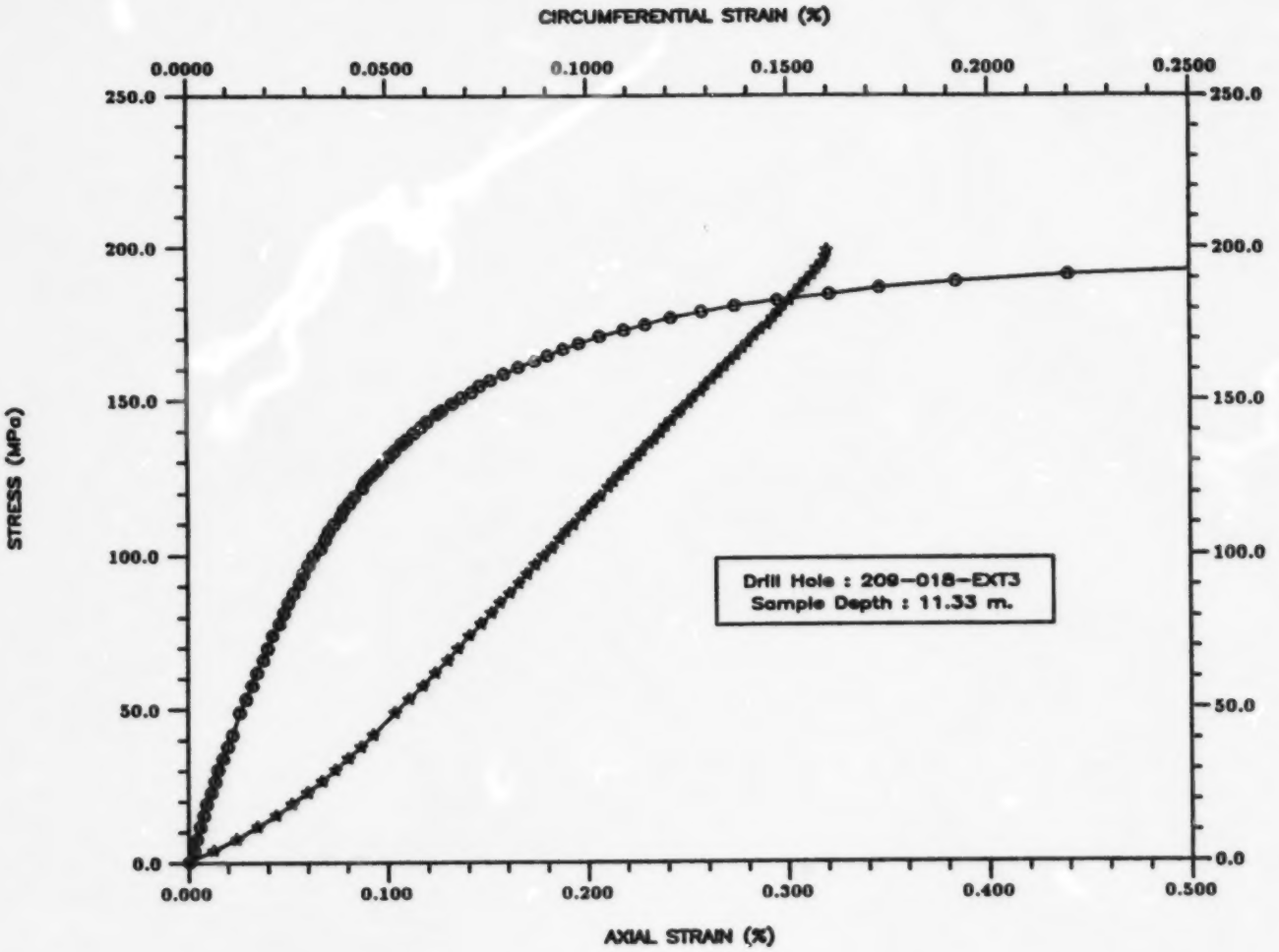

Figure 26: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

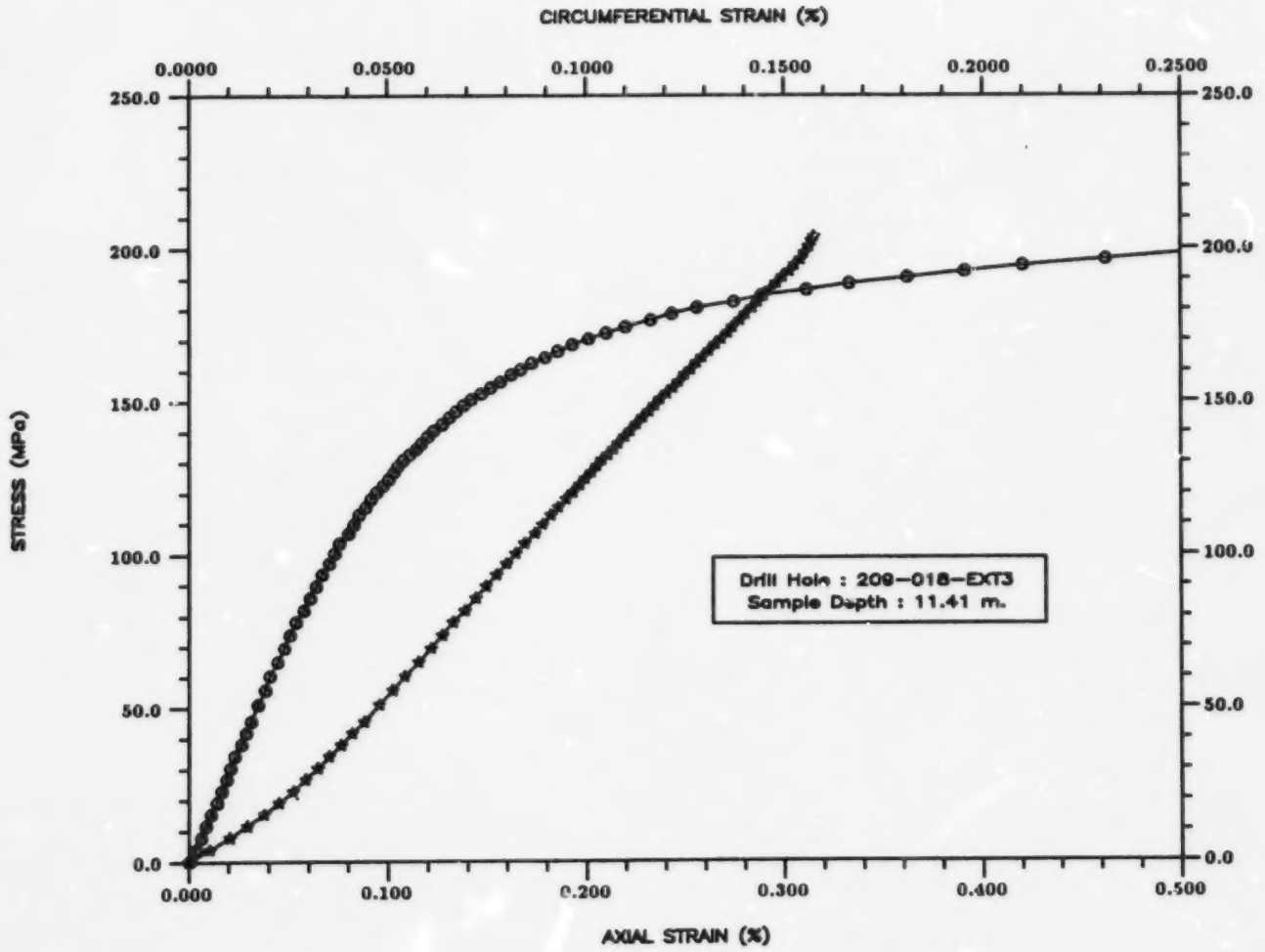

Figure 27: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

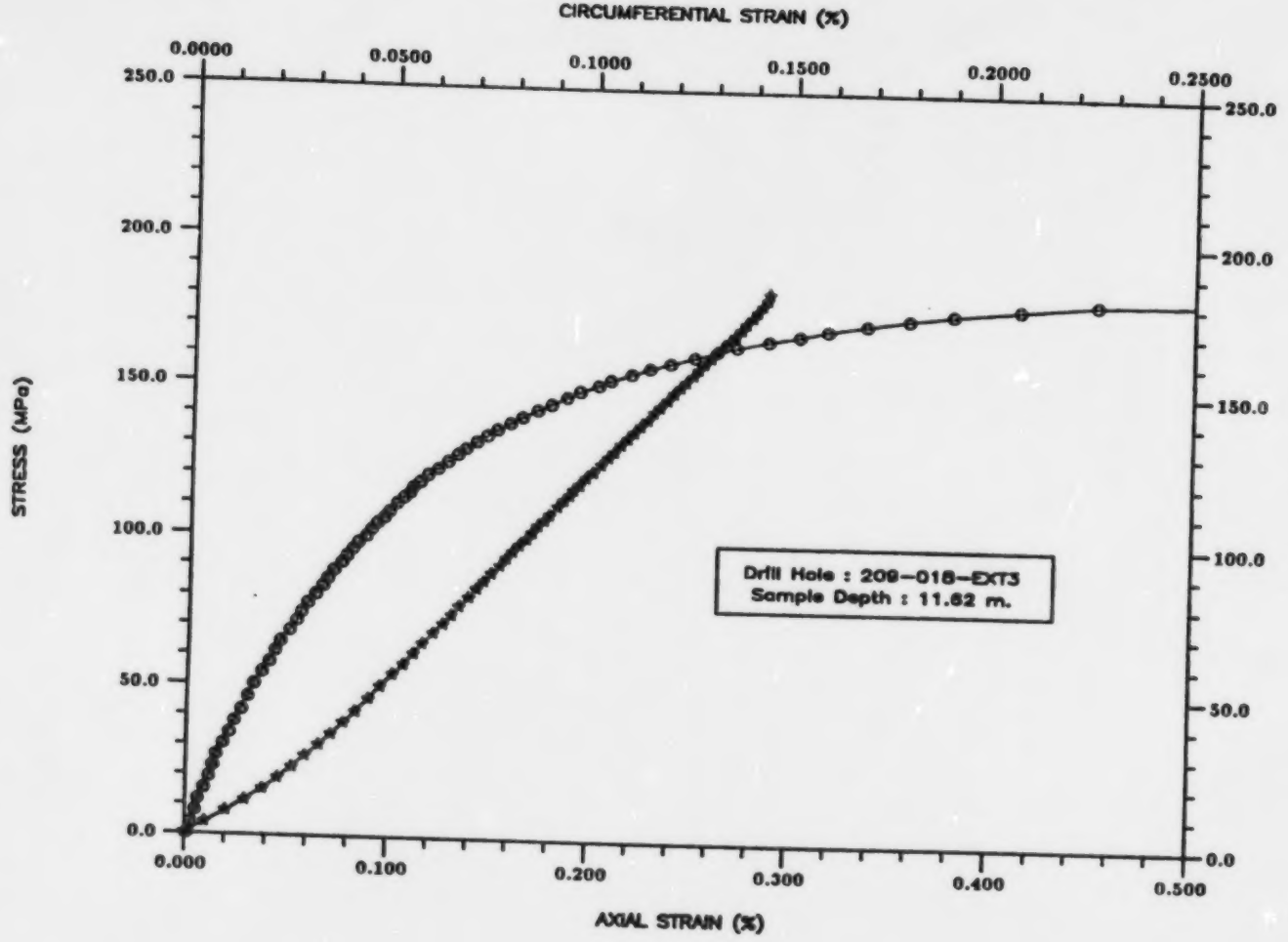

Figure 28: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

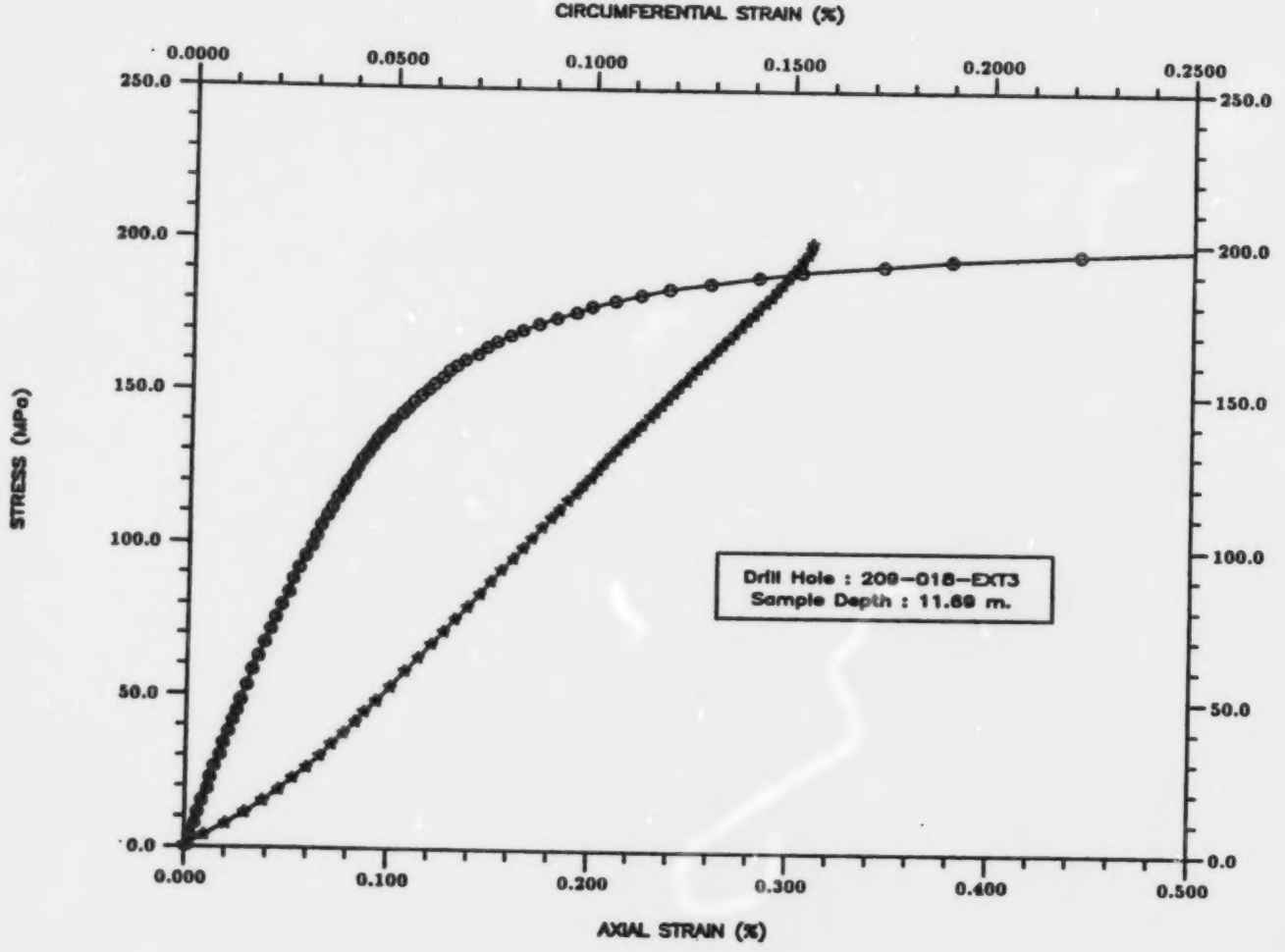

Figure 29: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

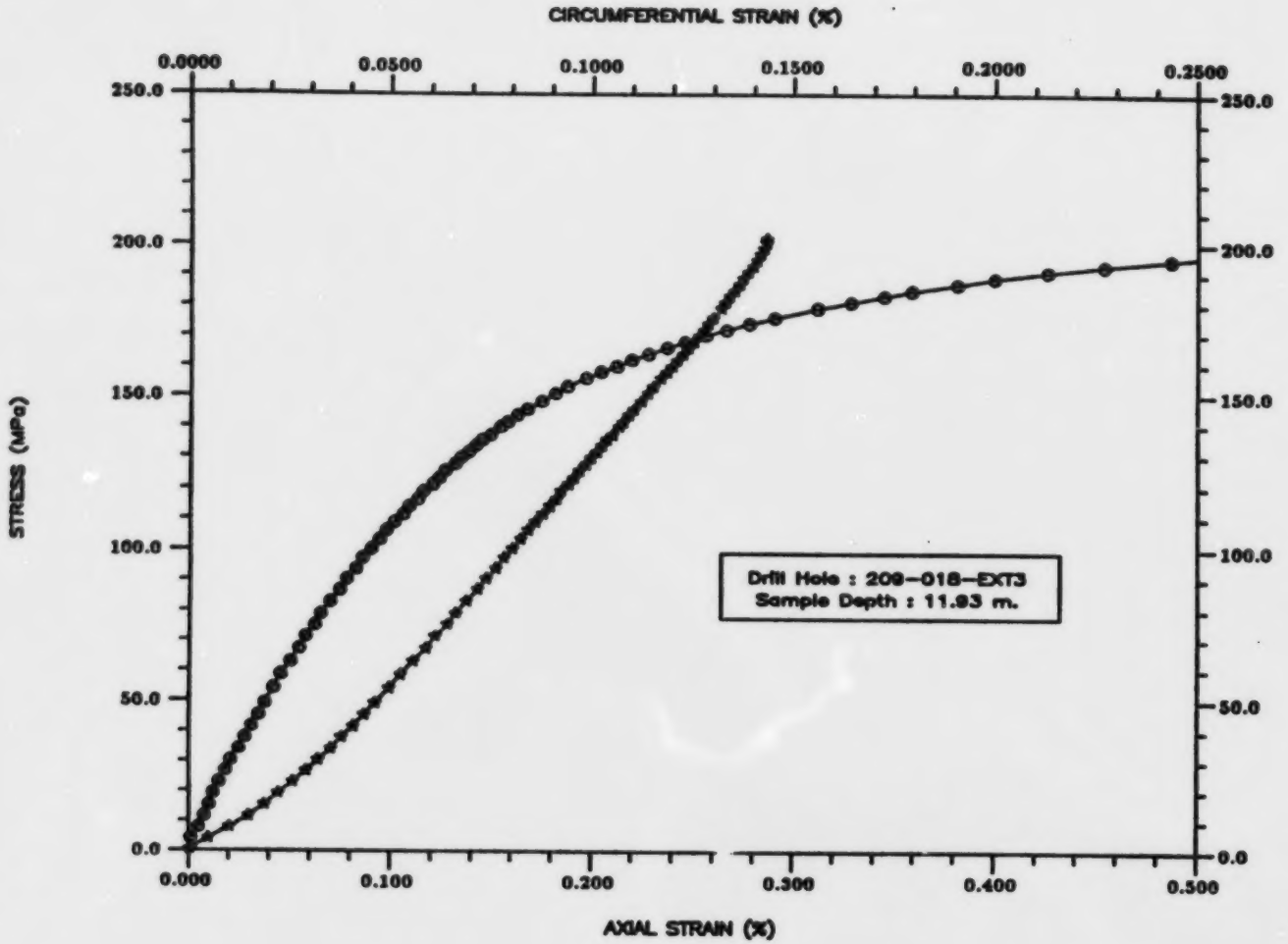

Figure 30: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

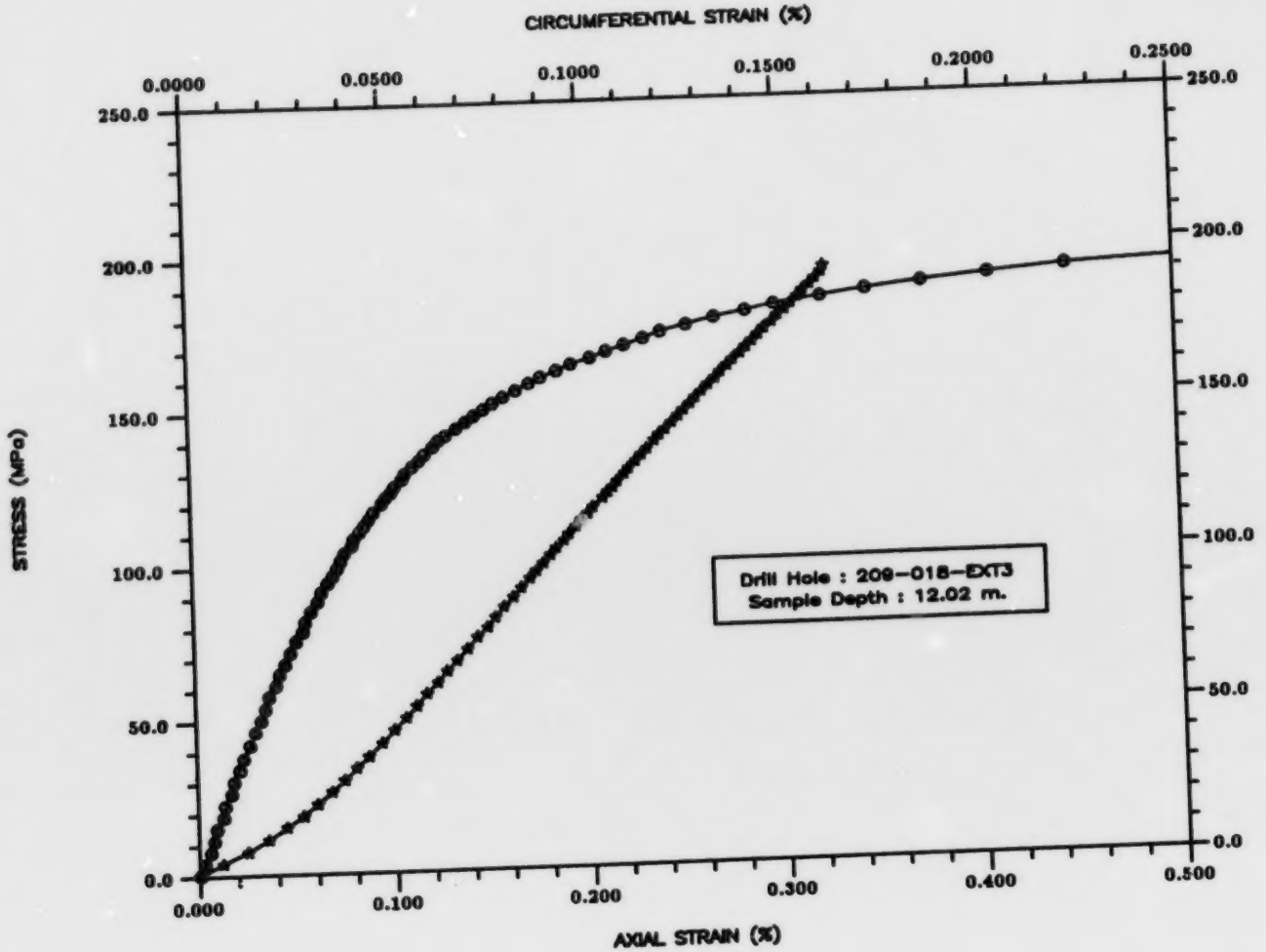

Figure 31: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

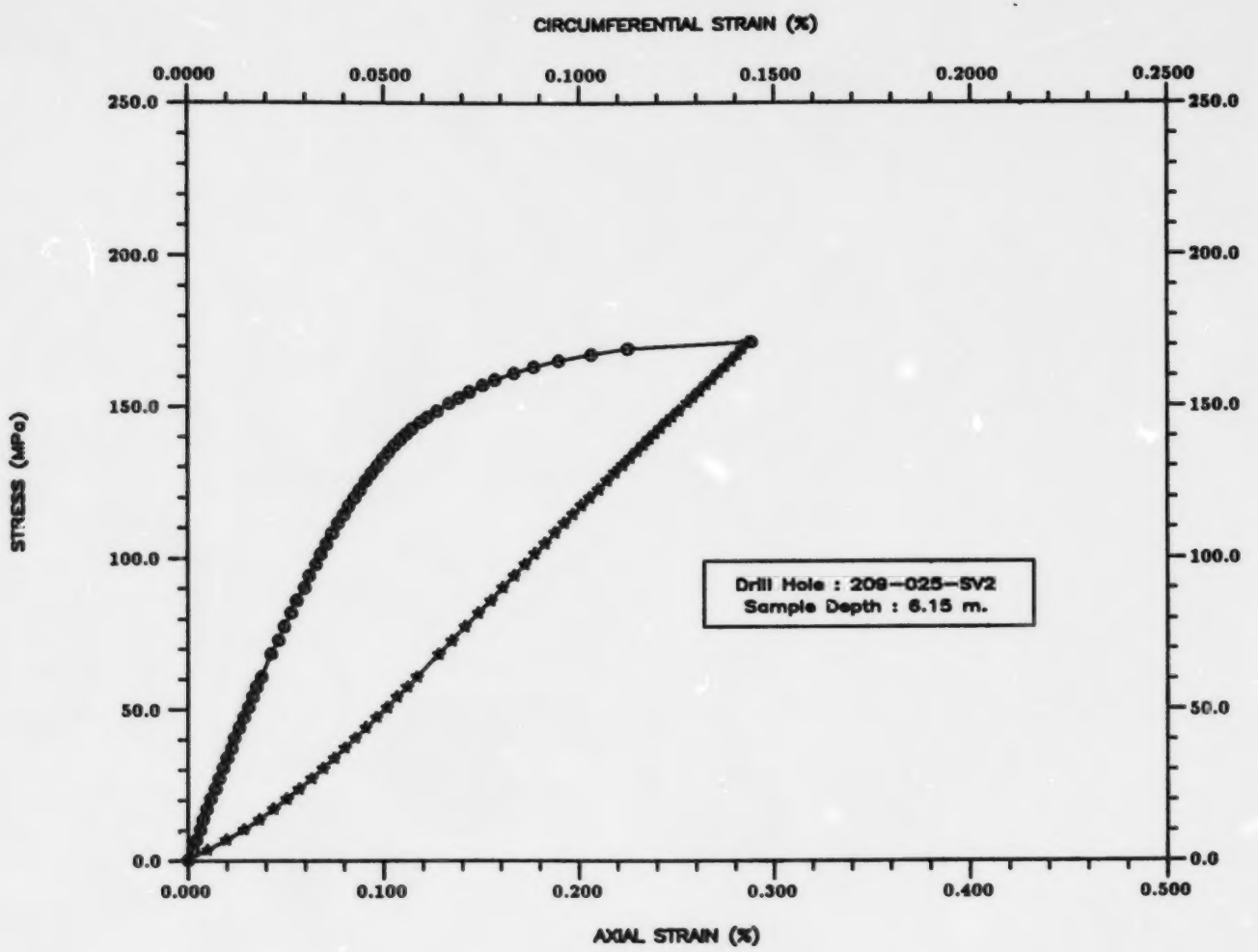

Figure 32: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

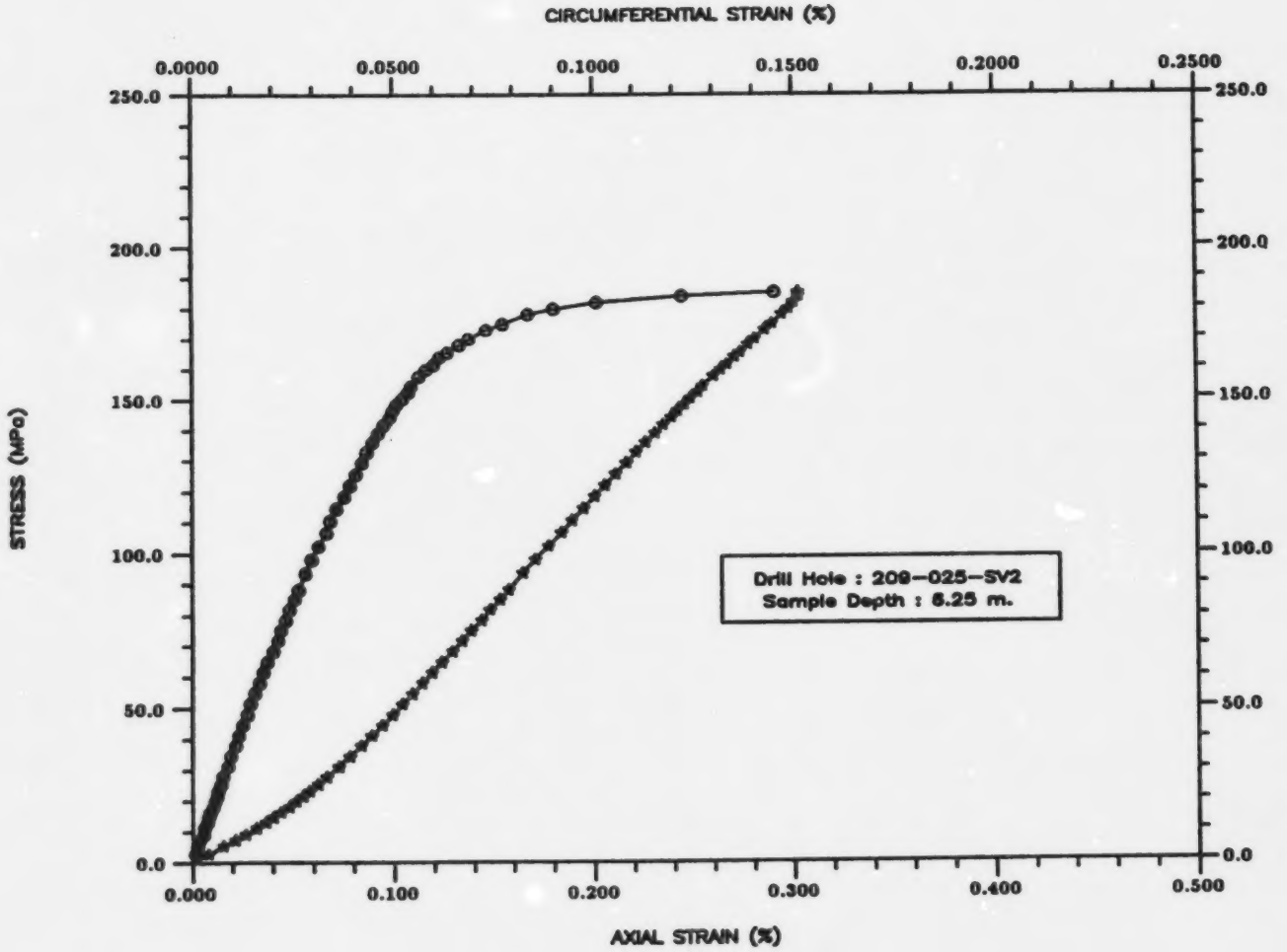

Figure 33: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

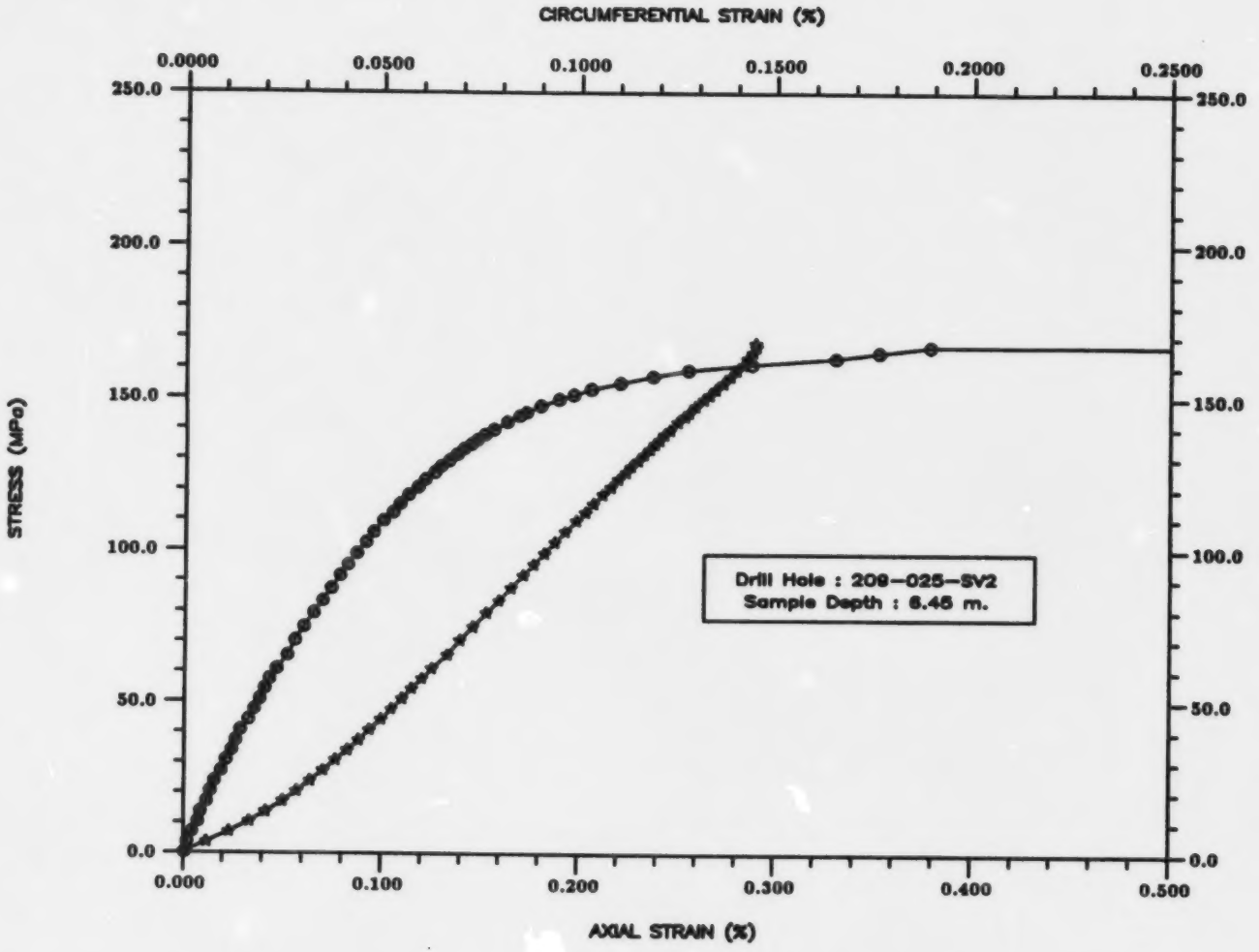

Figure 34: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

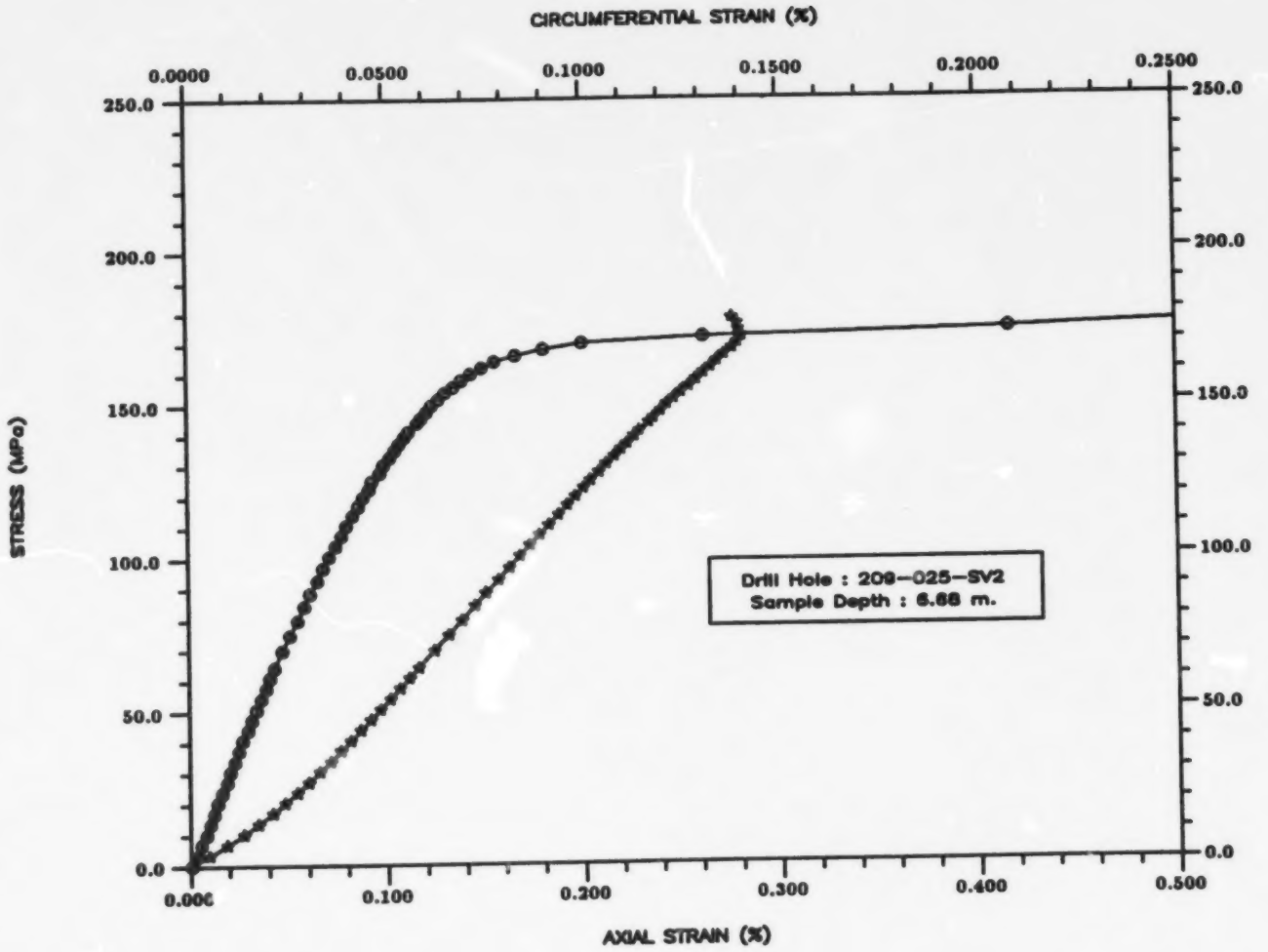

Figure 35: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

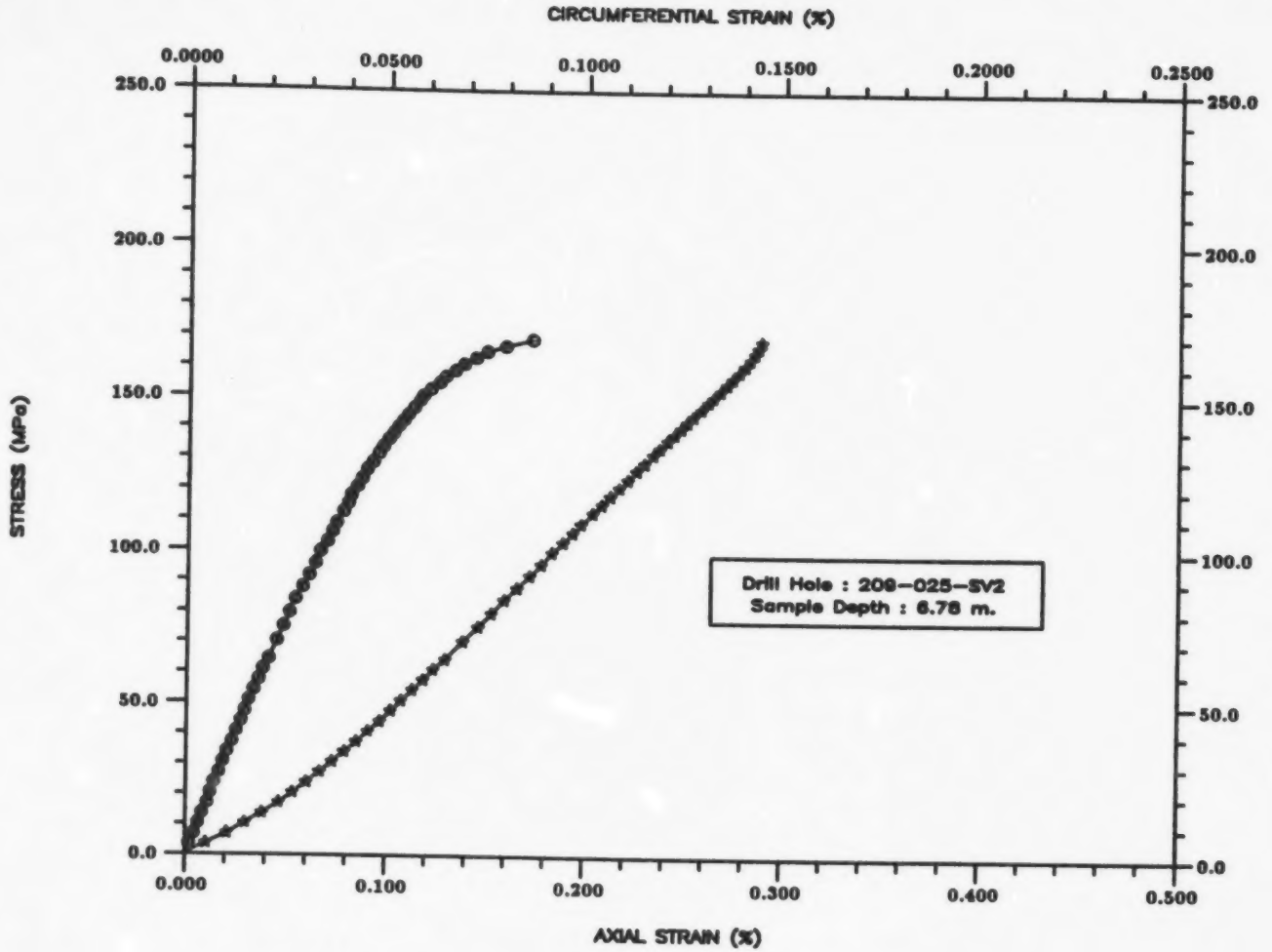

Figure 36: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

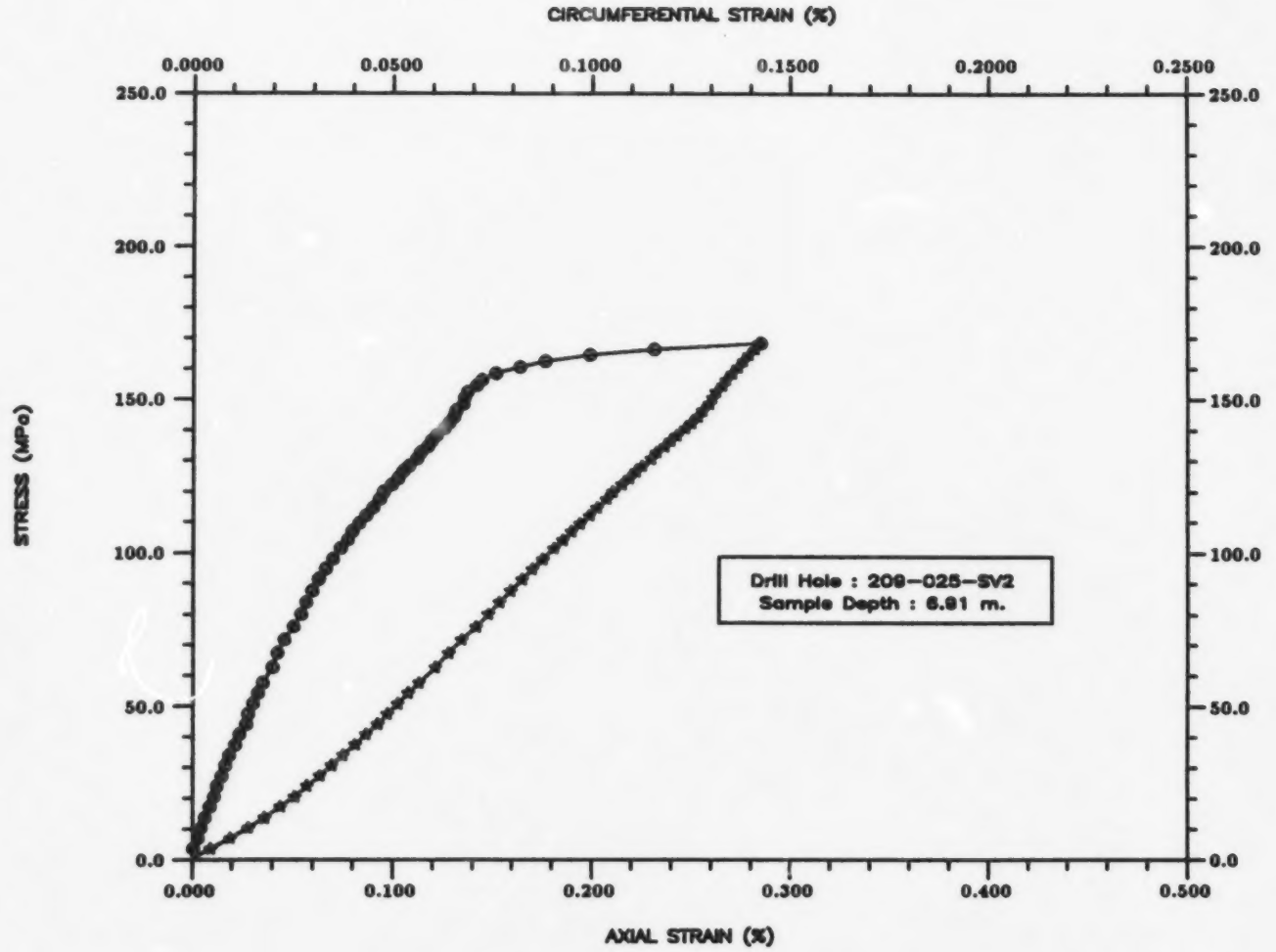

Figure 37: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

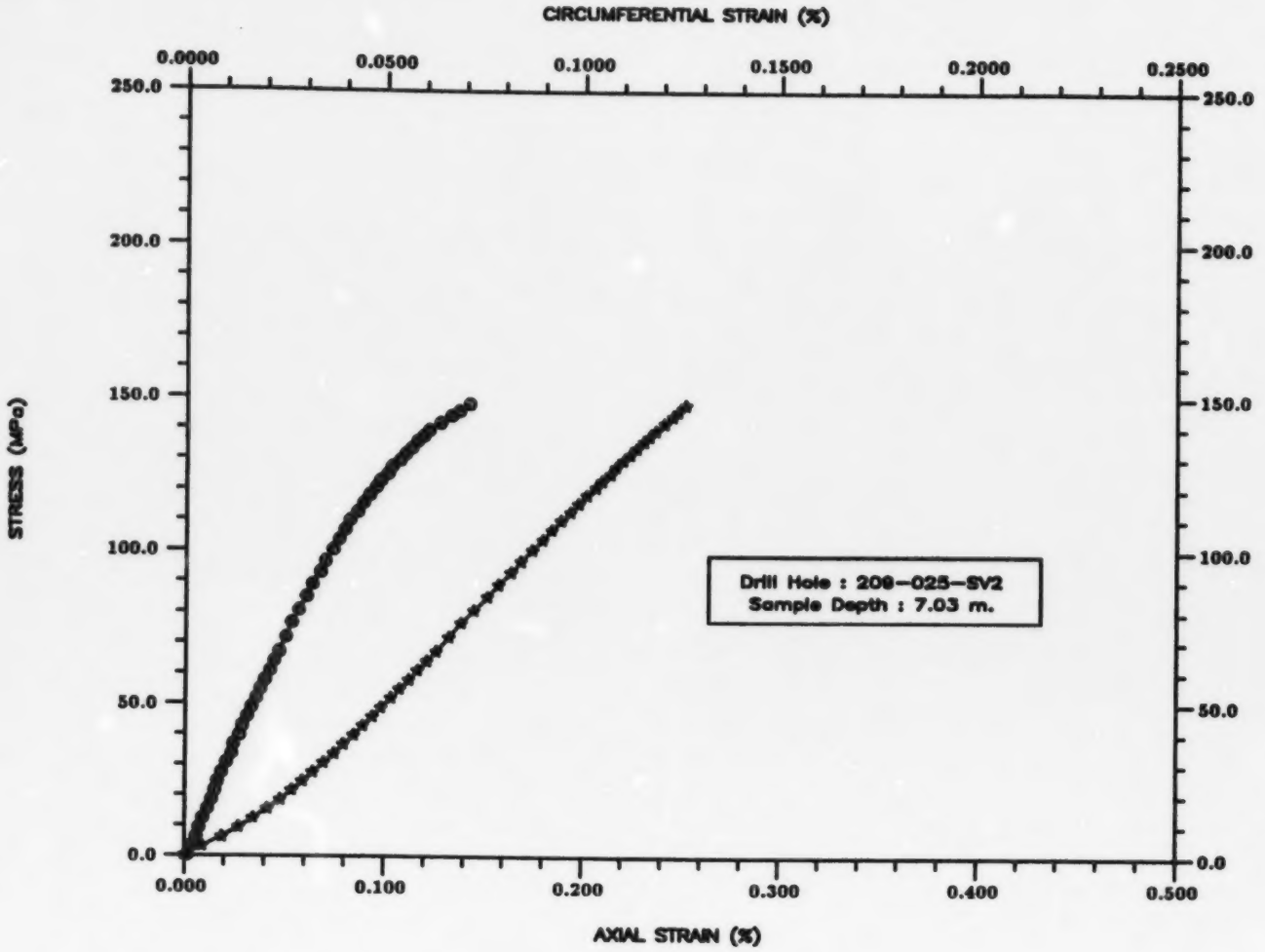

Figure 38: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

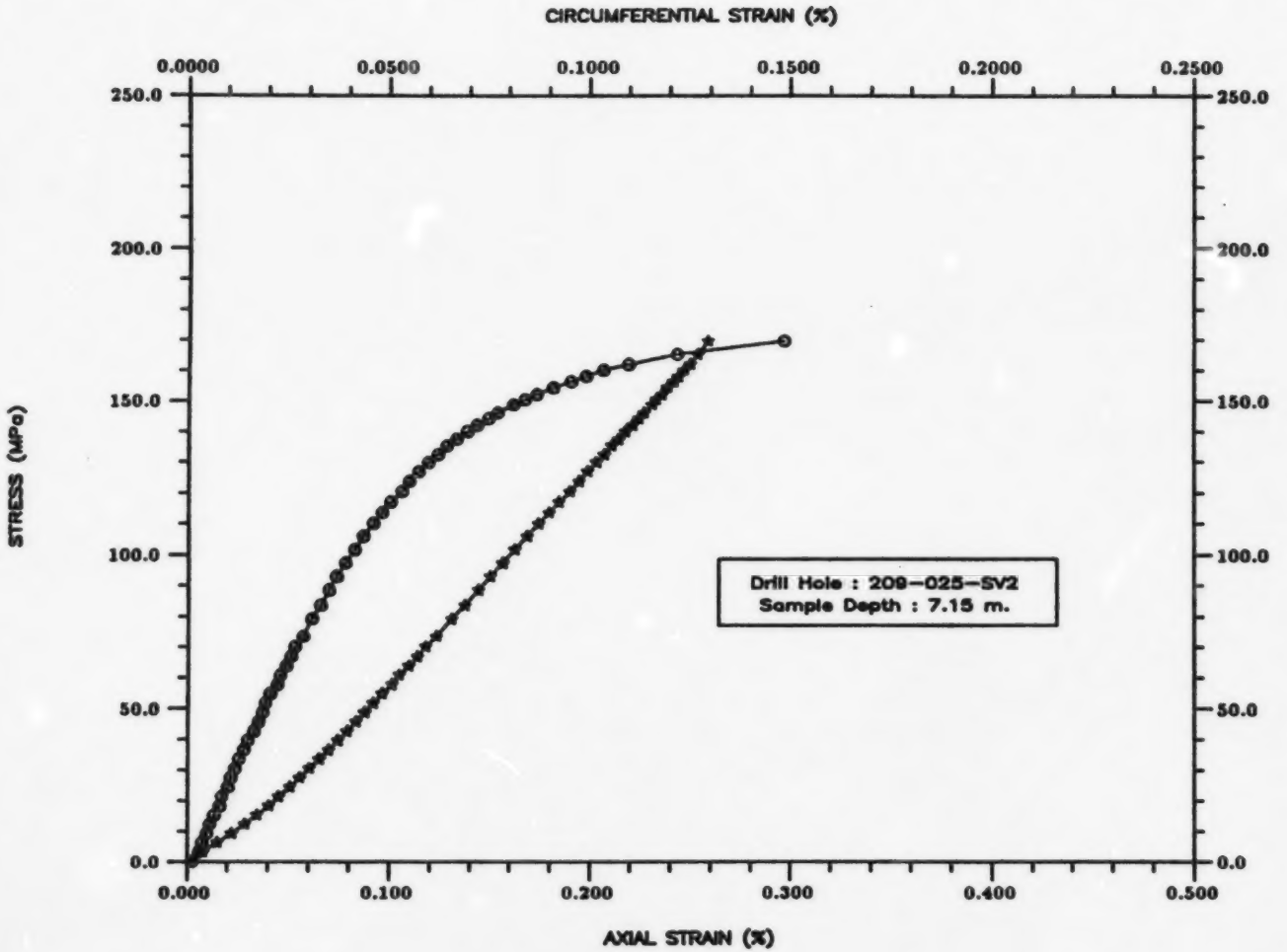

Figure 39: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

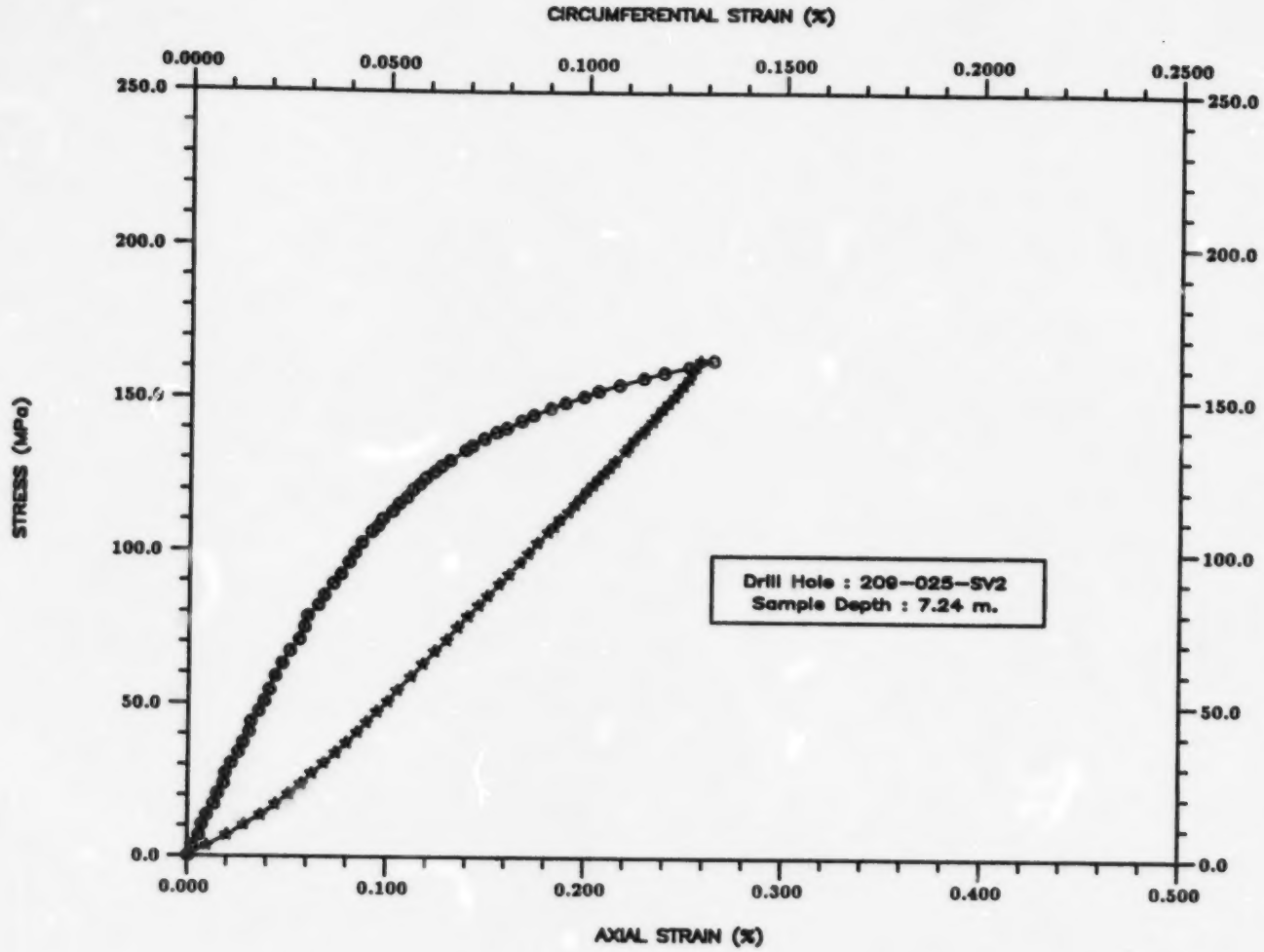

Figure 40: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

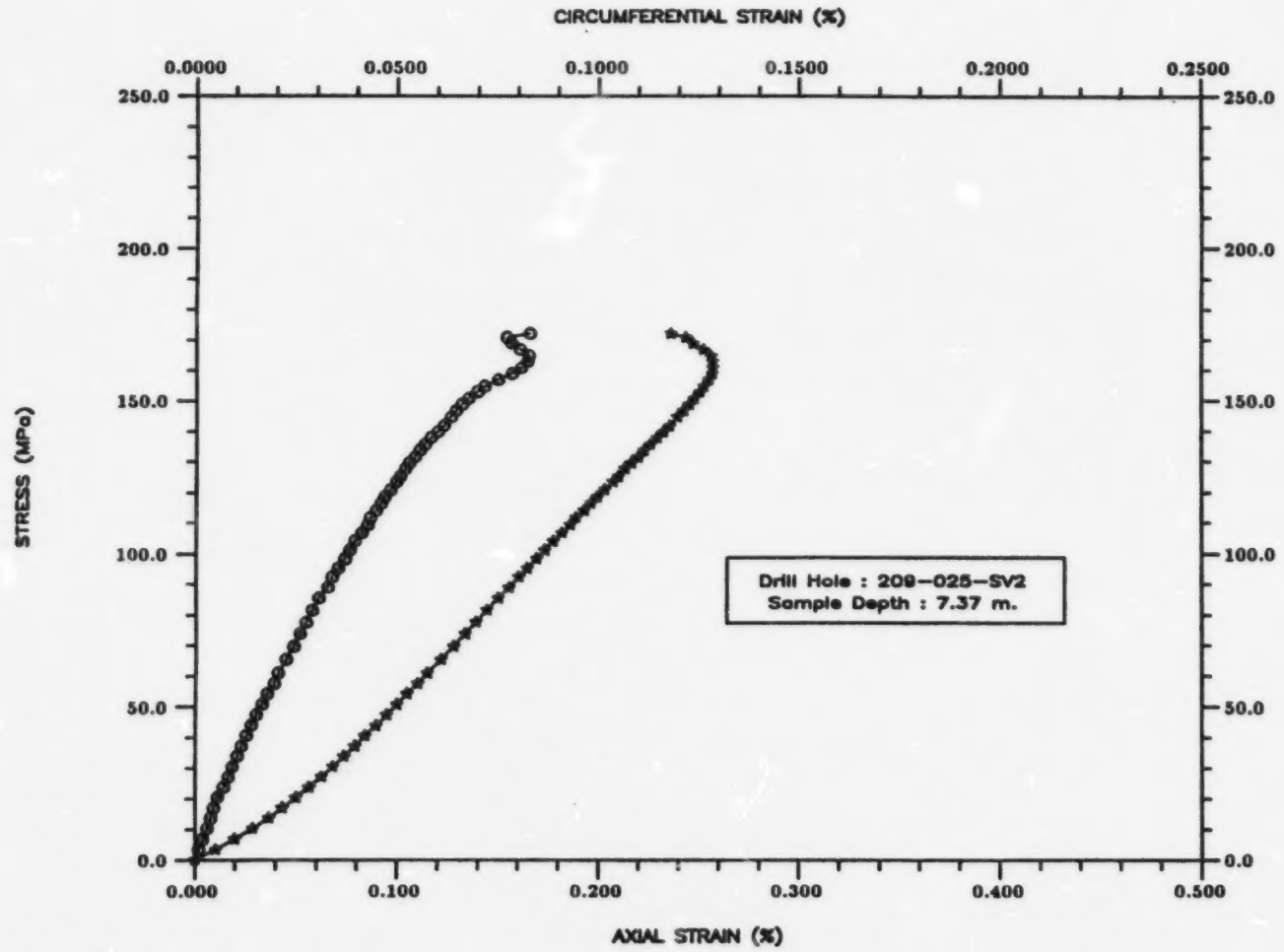

Figure 41: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

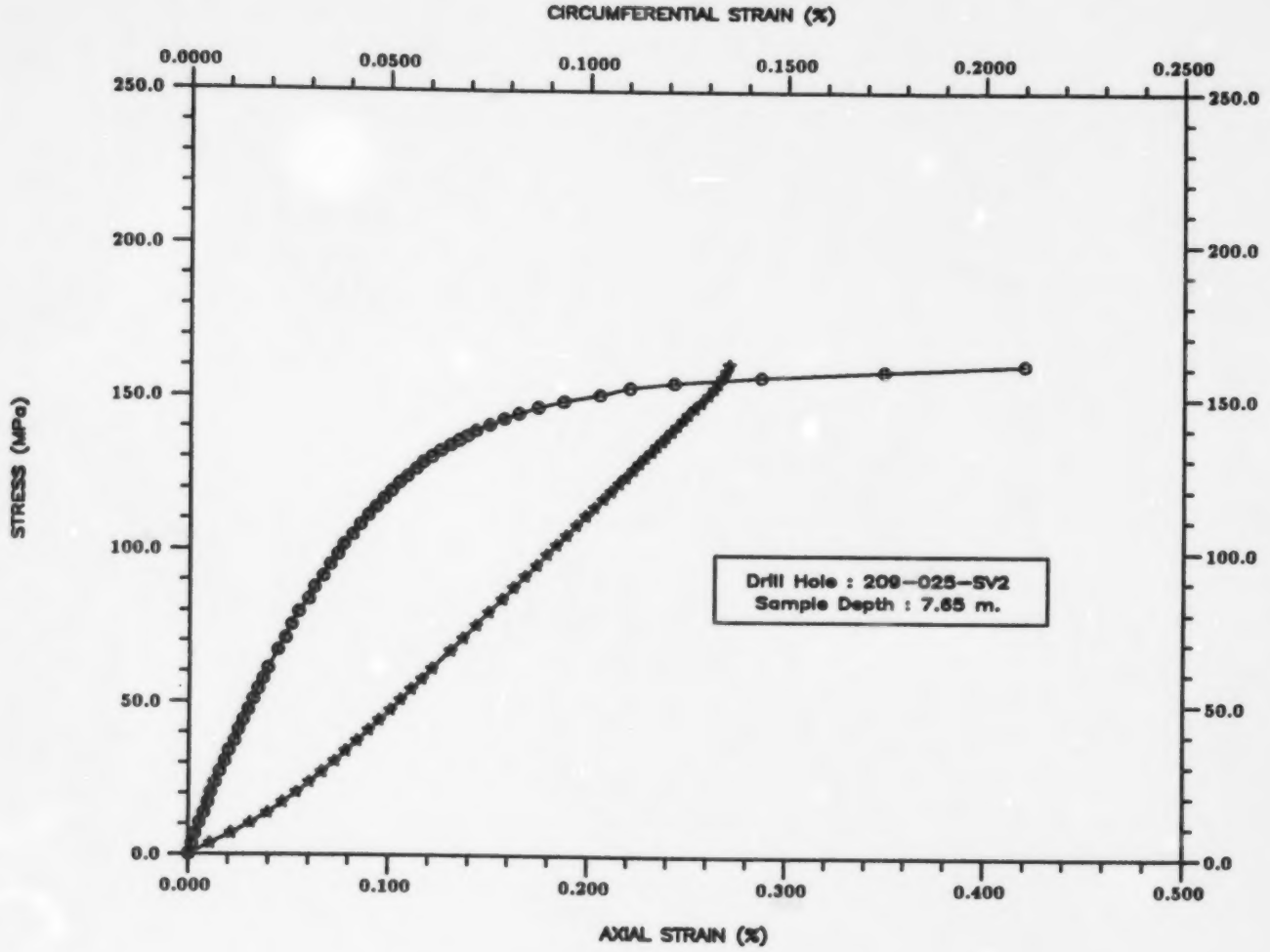

Figure 42: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

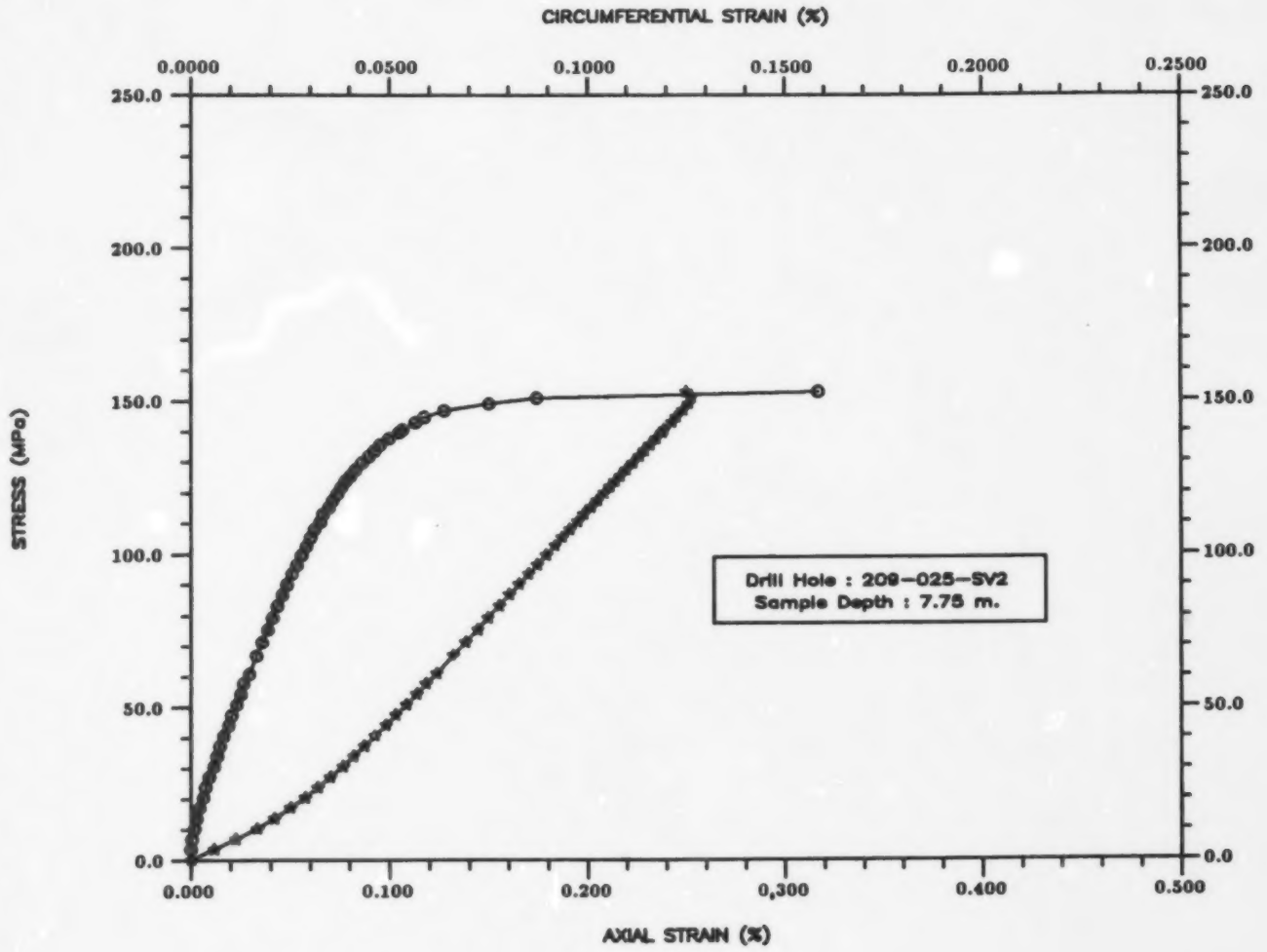

Figure 43: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

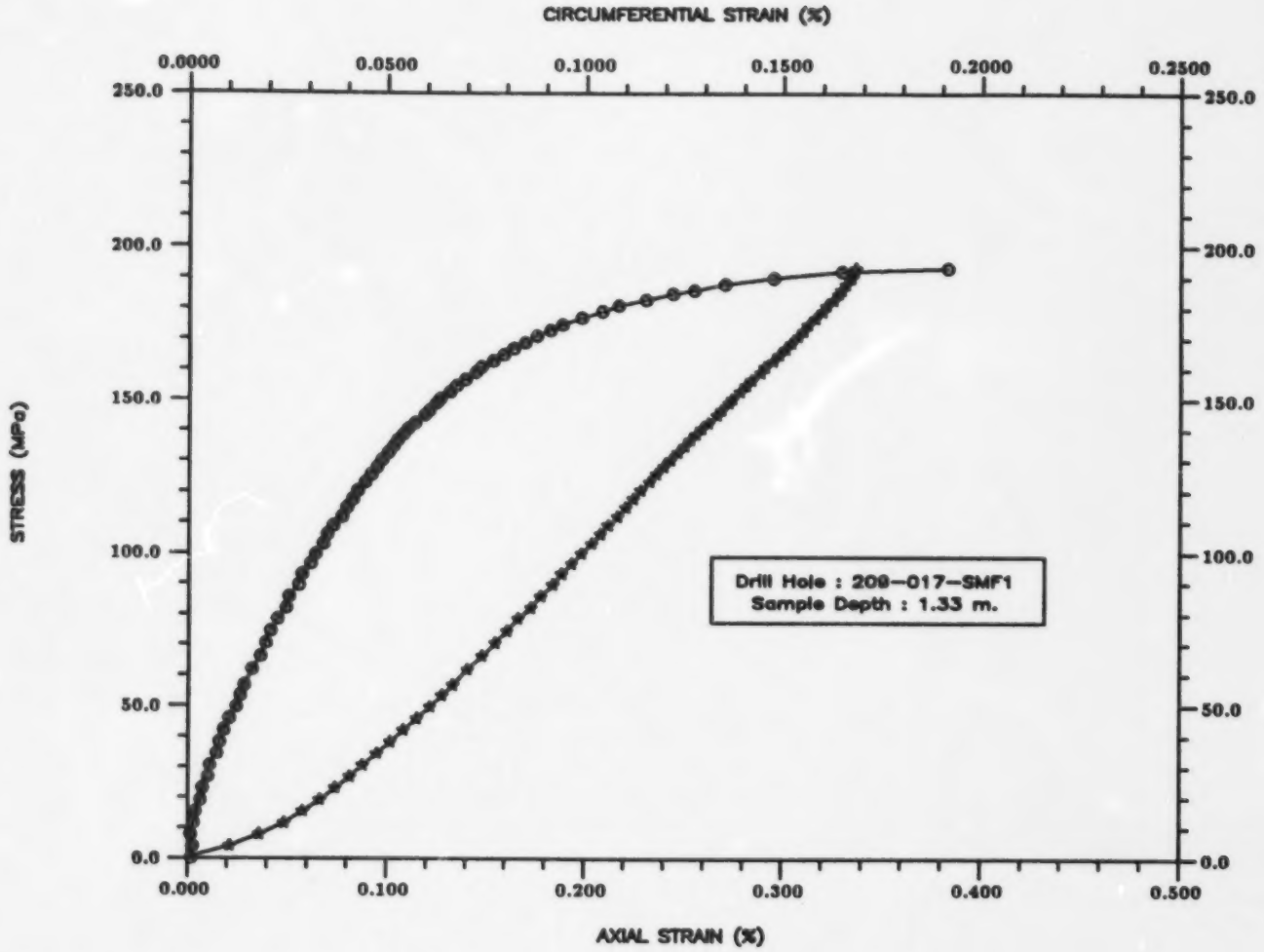

Figure 44: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

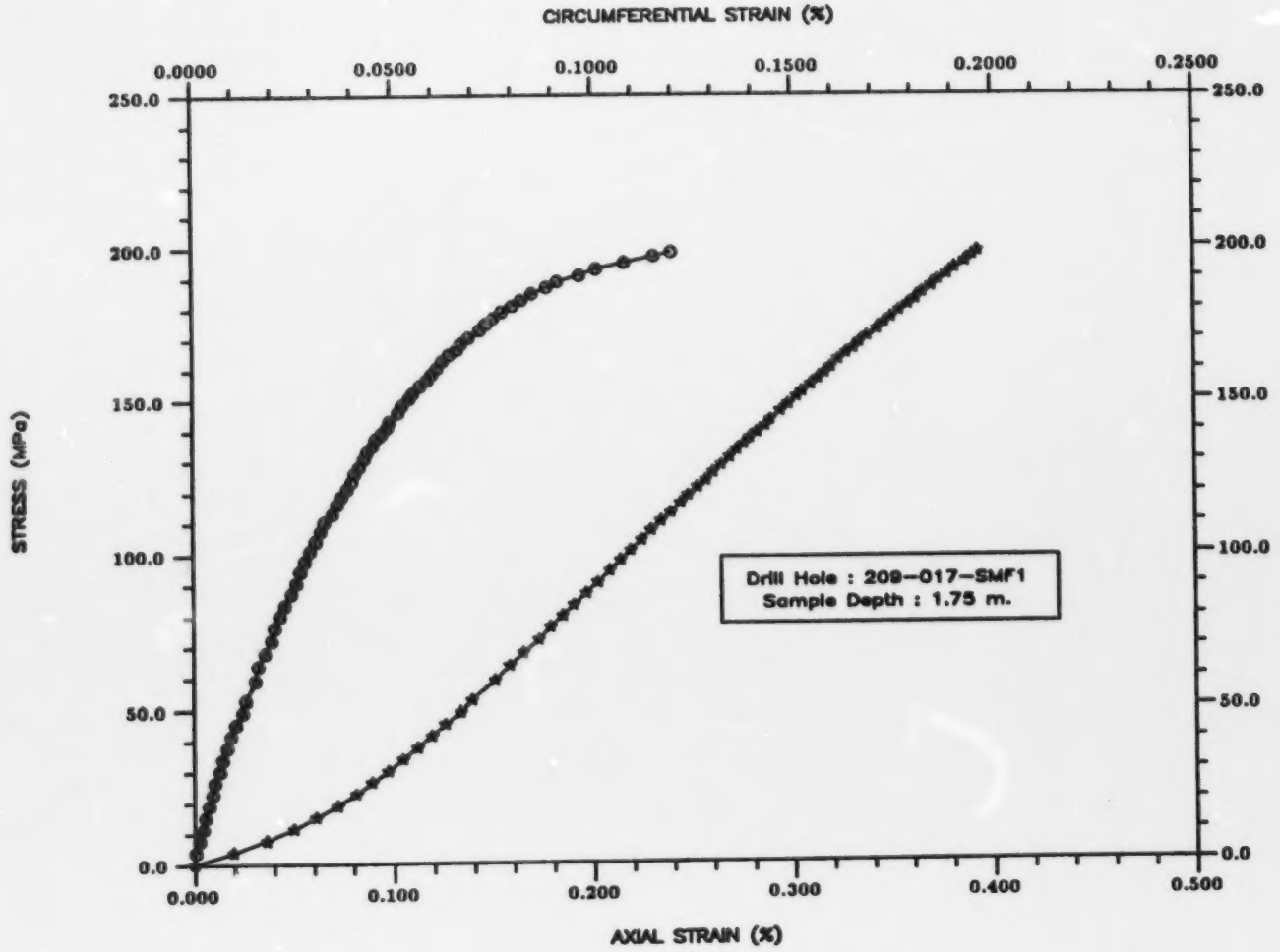

Figure 45: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

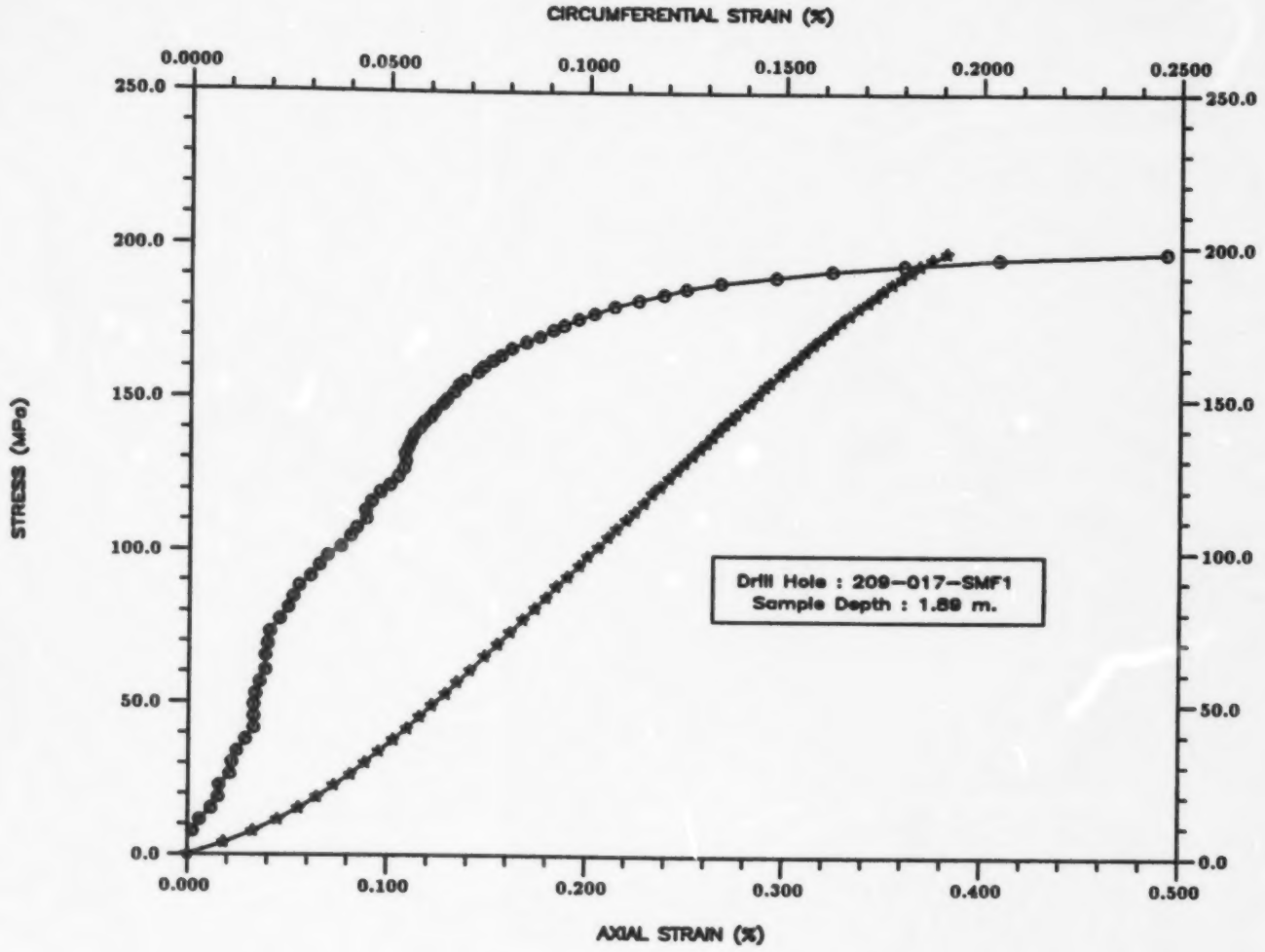

Figure 46: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

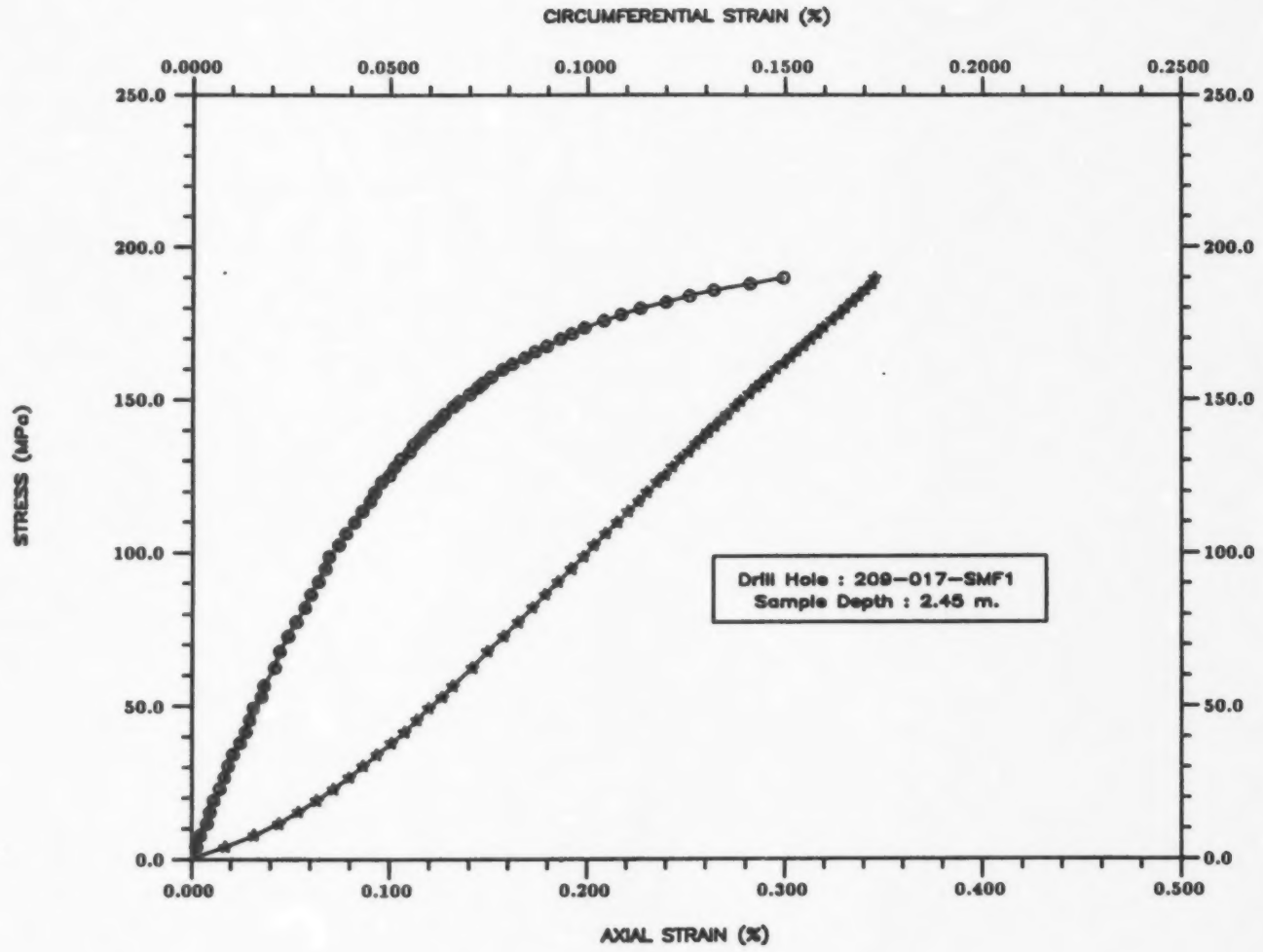

Figure 47: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

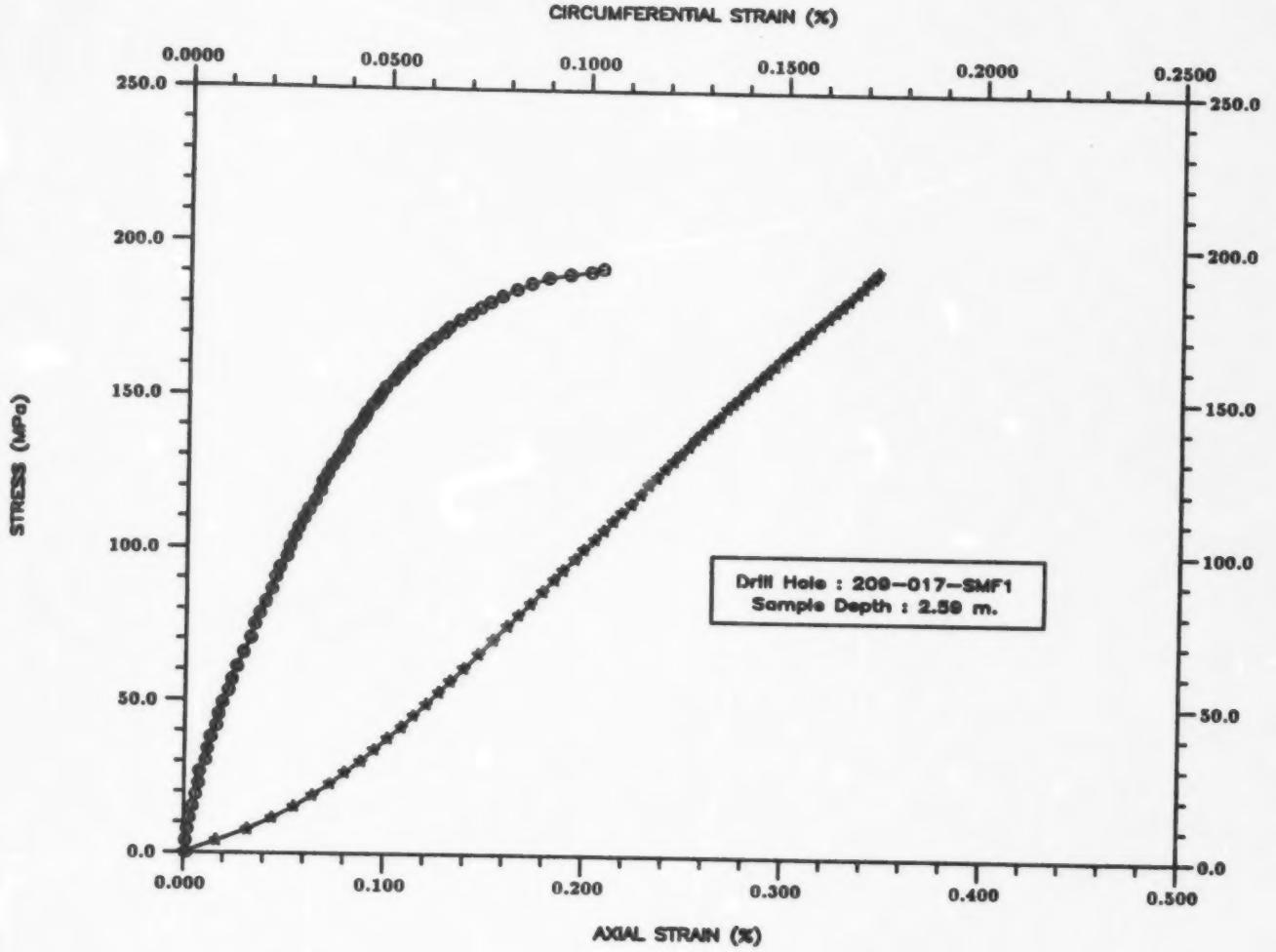

Figure 48: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

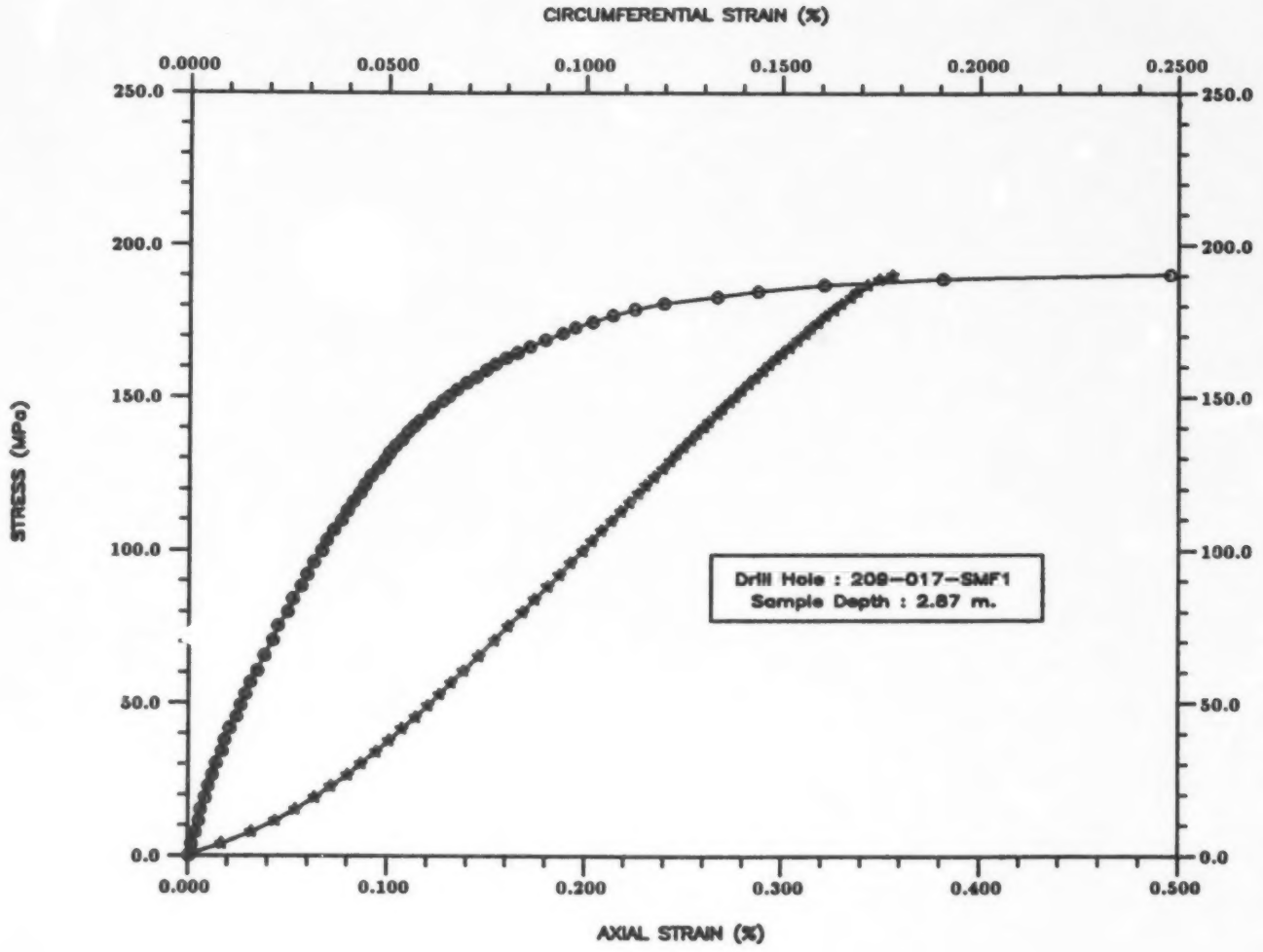

Figure 49: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

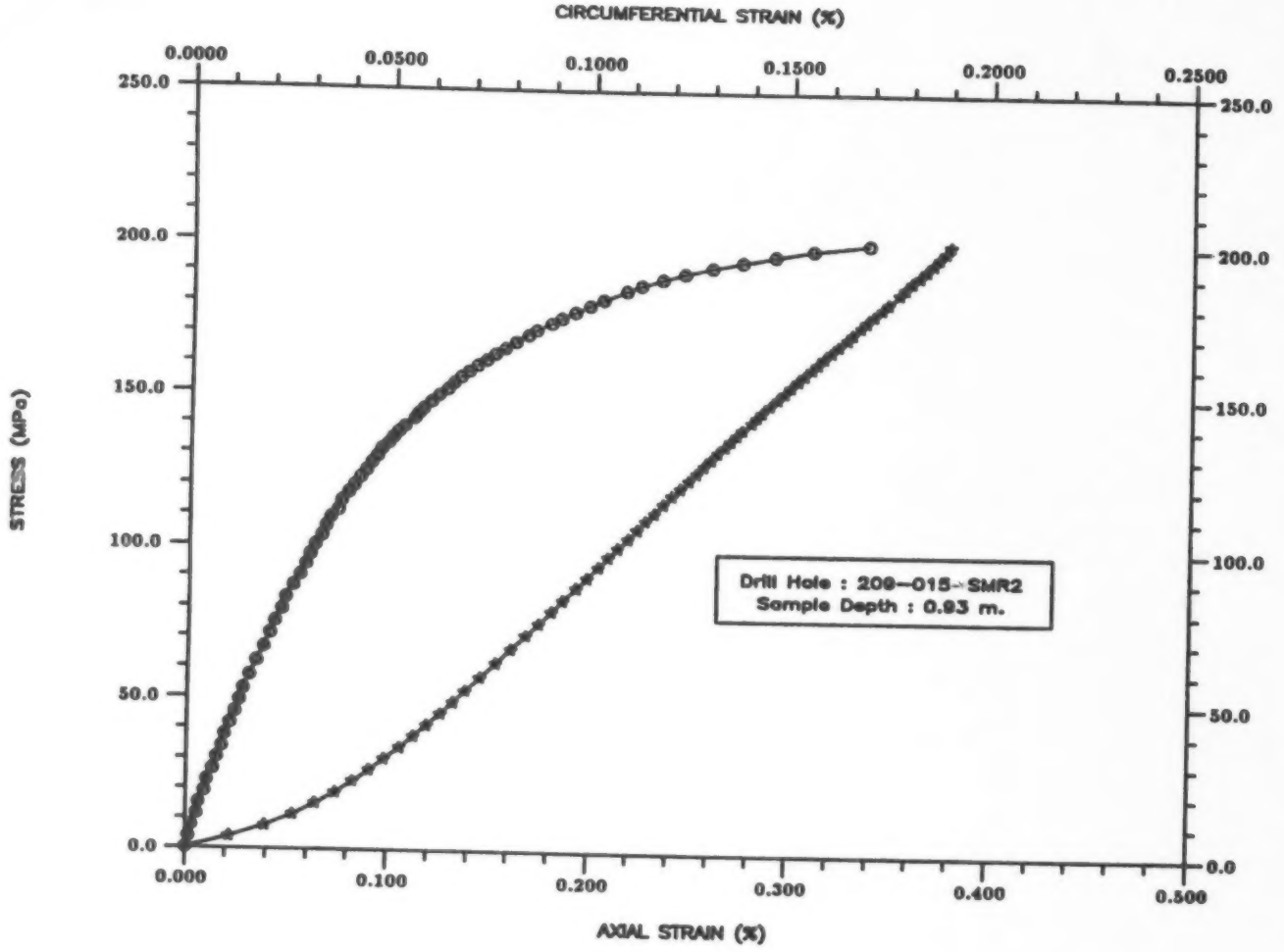

Figure 50: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

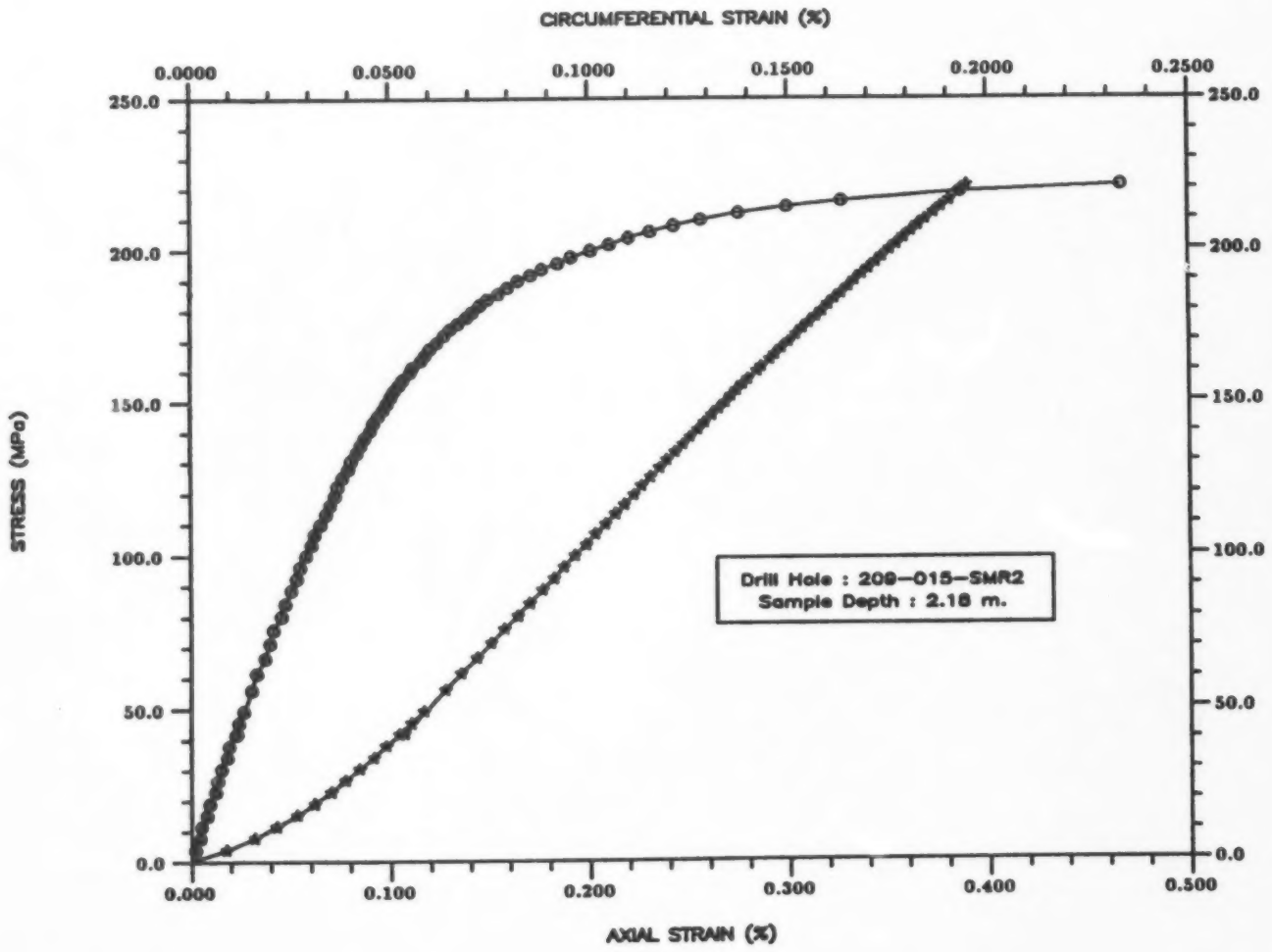

Figure 51: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

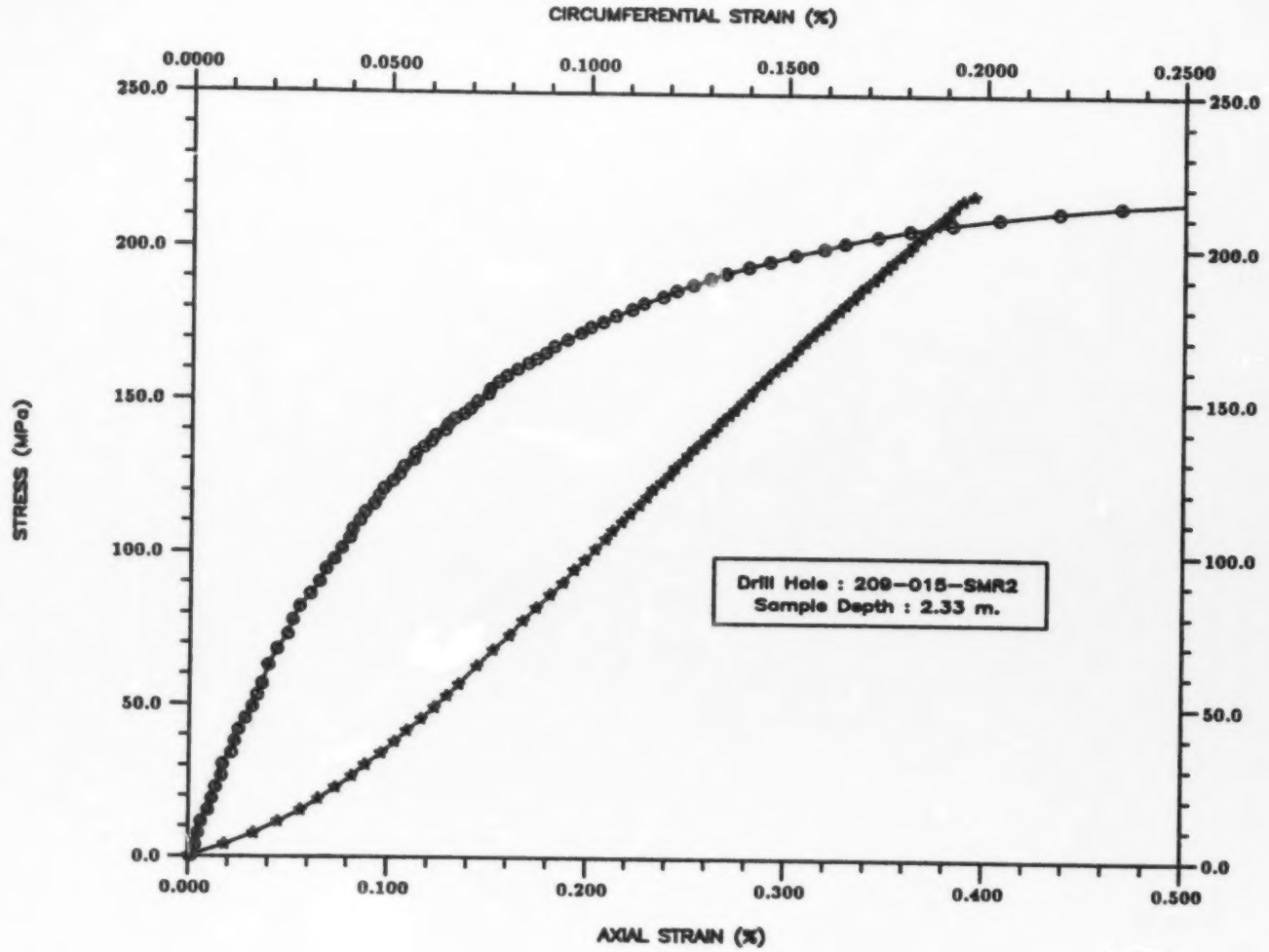

Figure 52: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

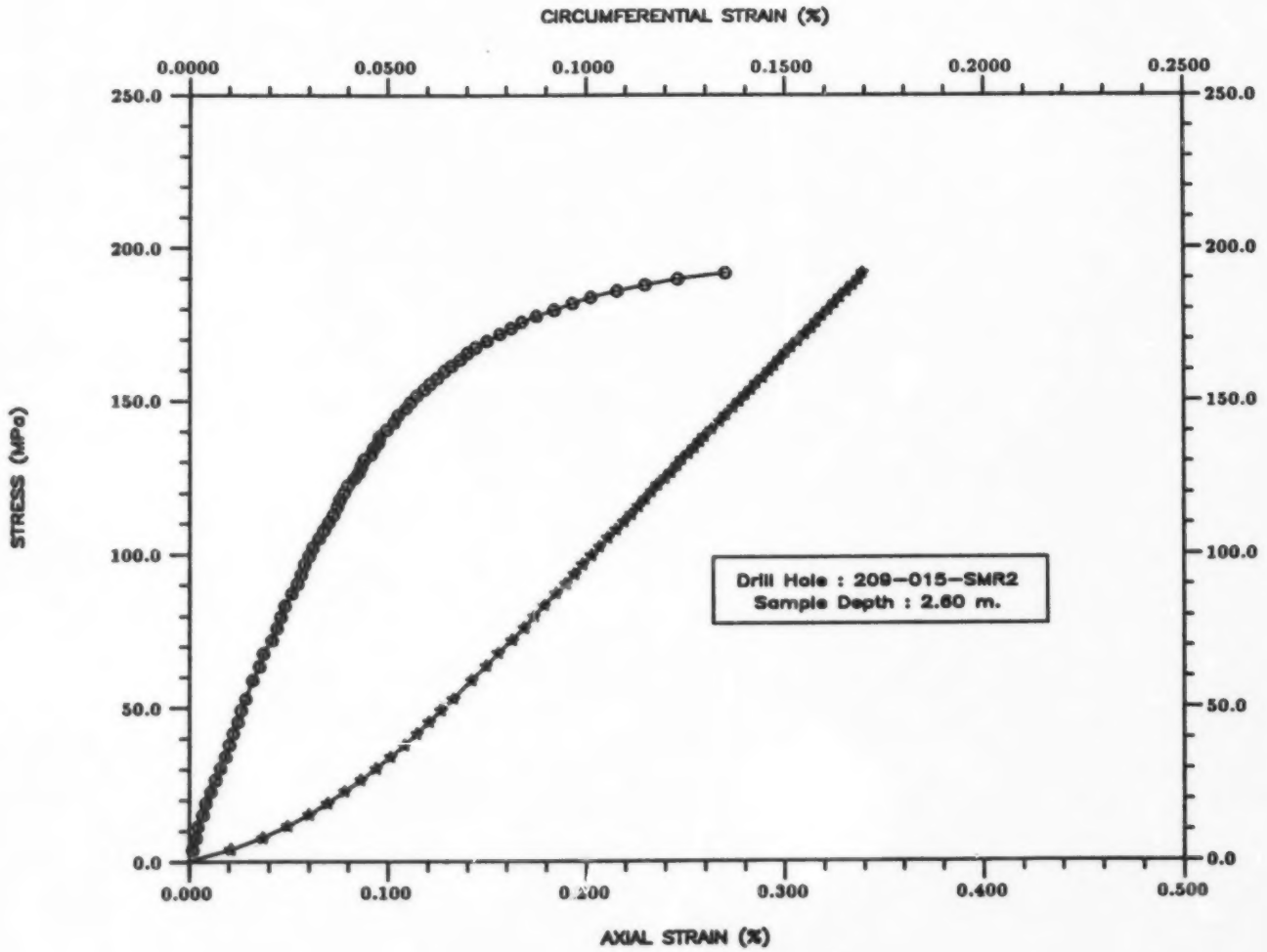

Figure 53: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

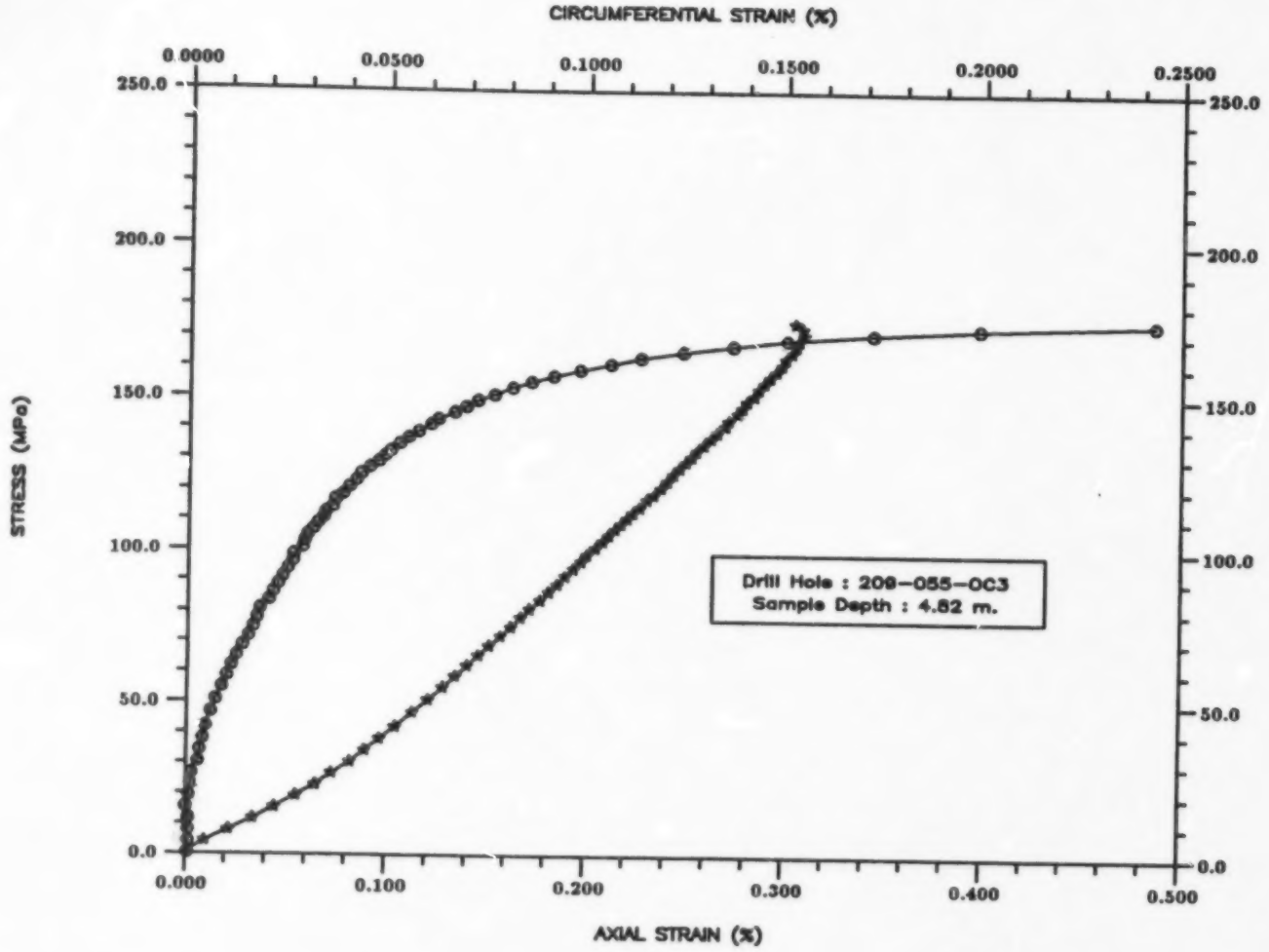

Figure 54: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

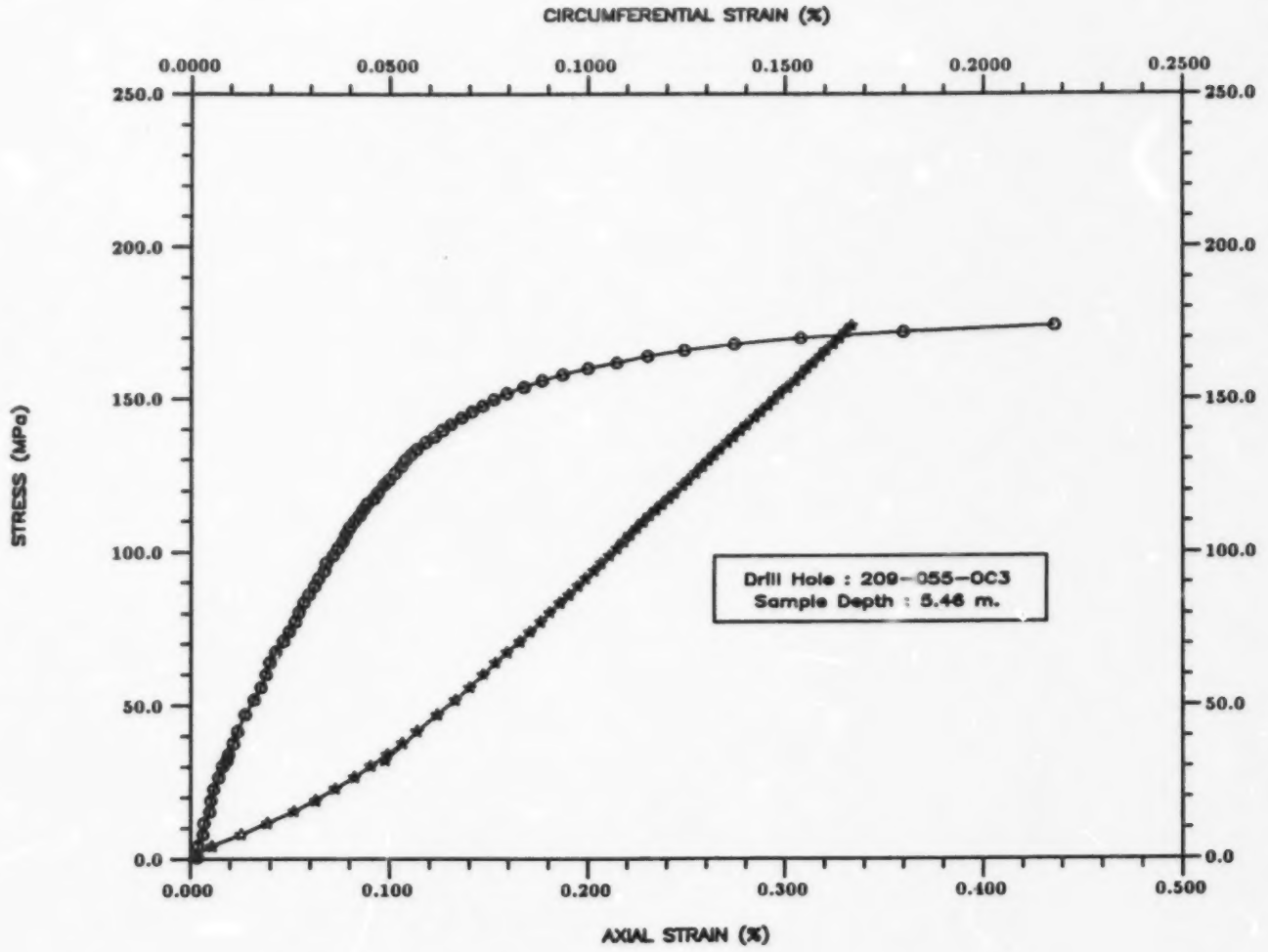

Figure 55: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

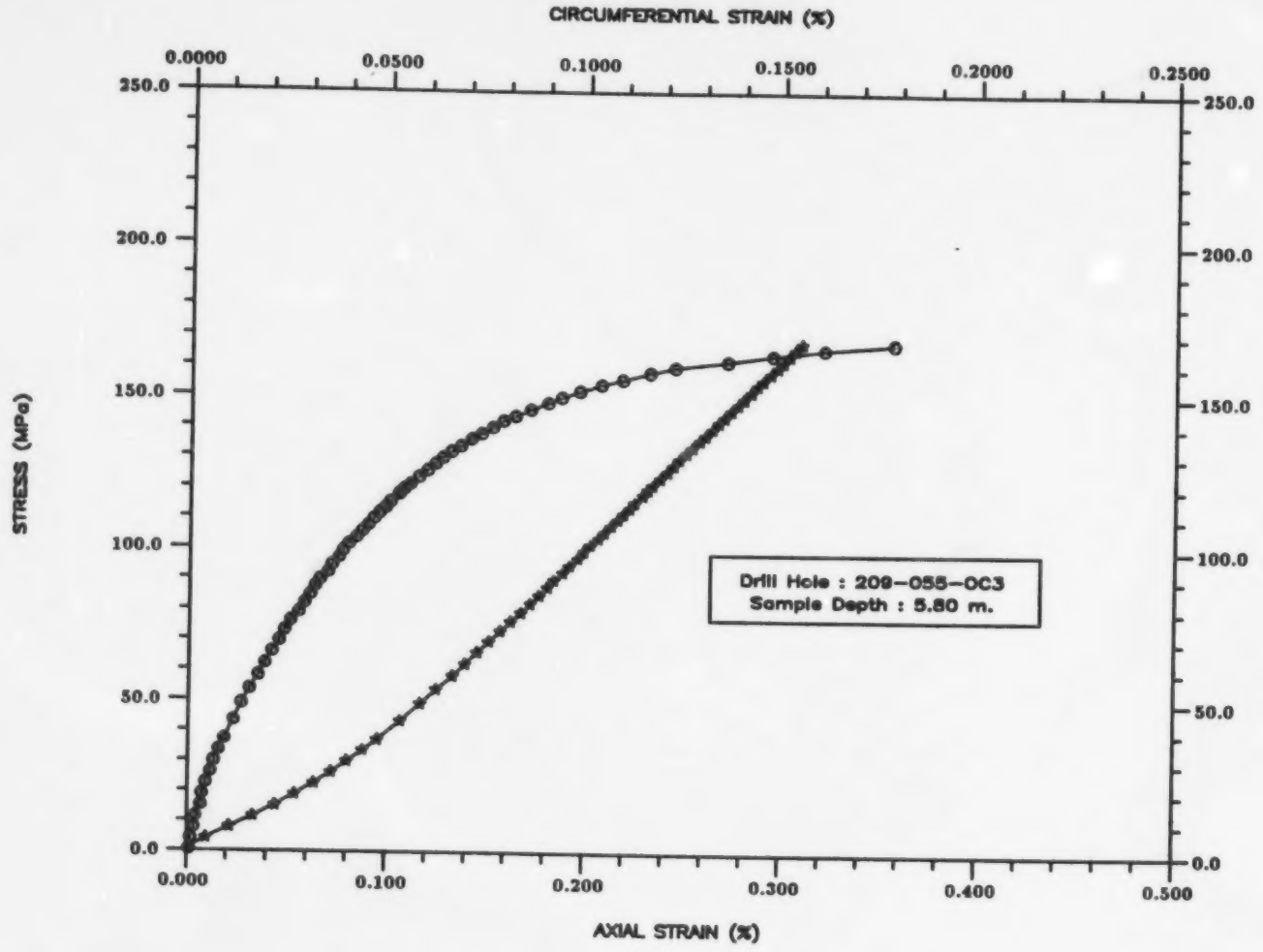

Figure 56: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

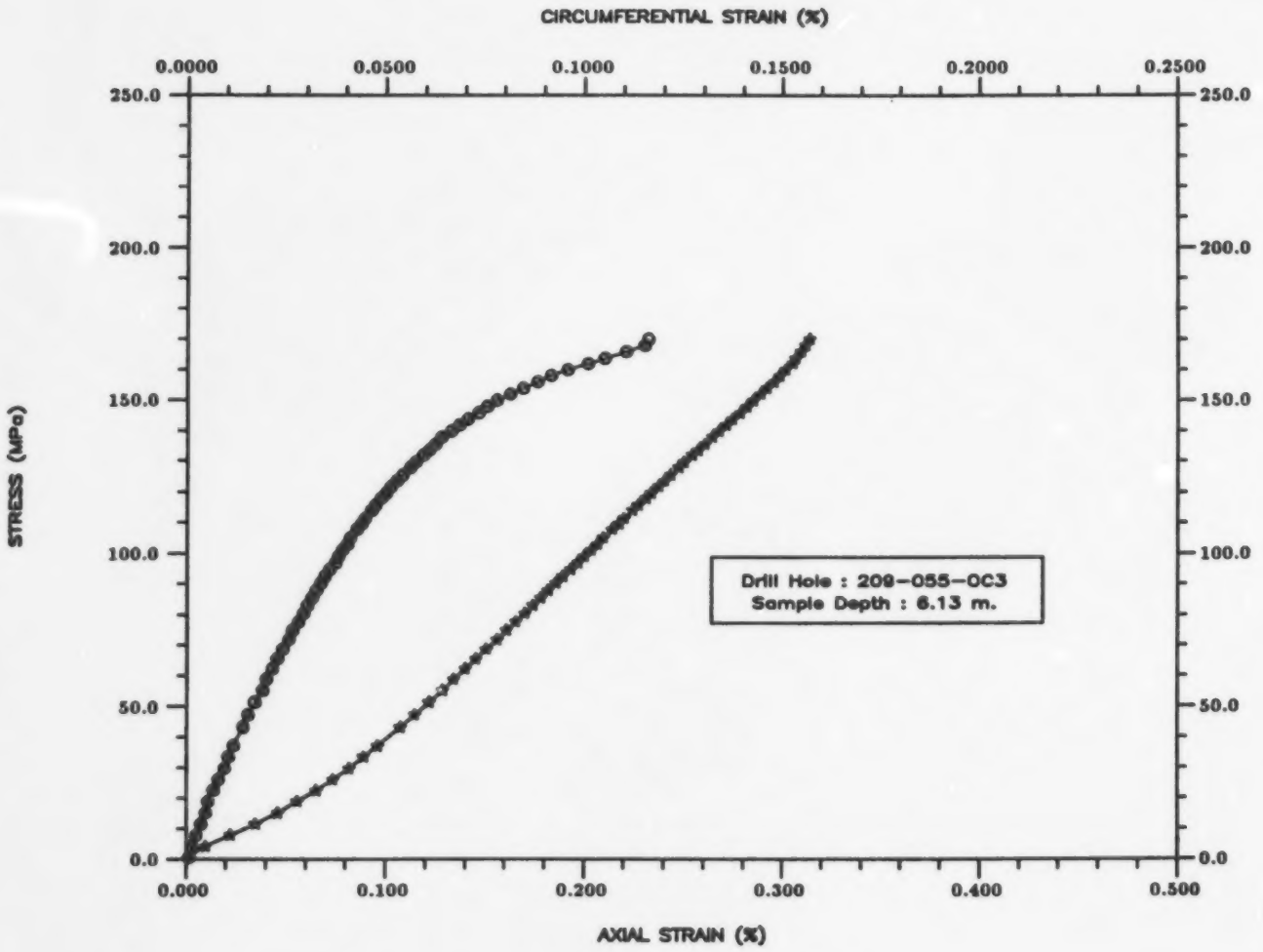

Figure 57: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

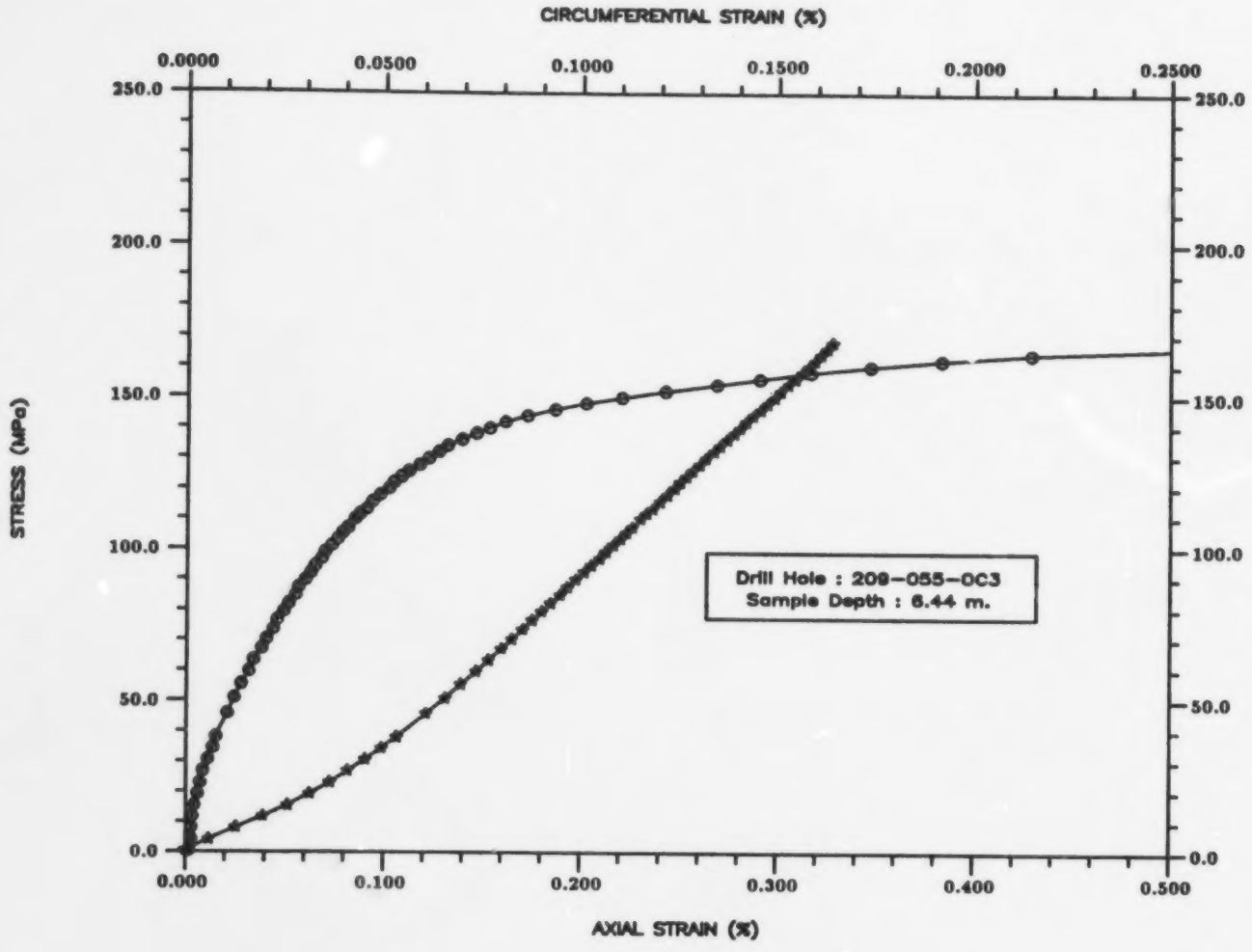

Figure 58: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

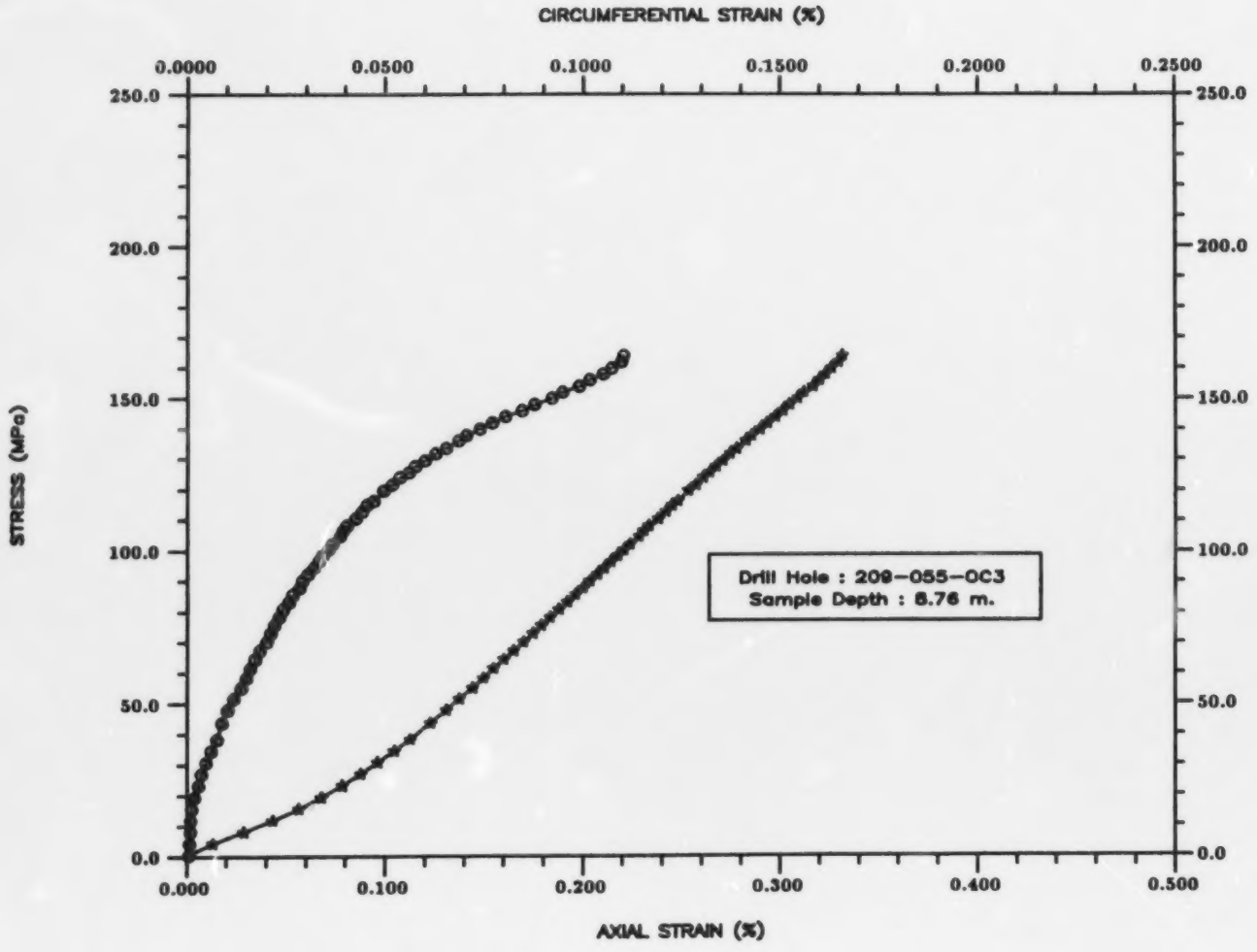

Figure 59: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

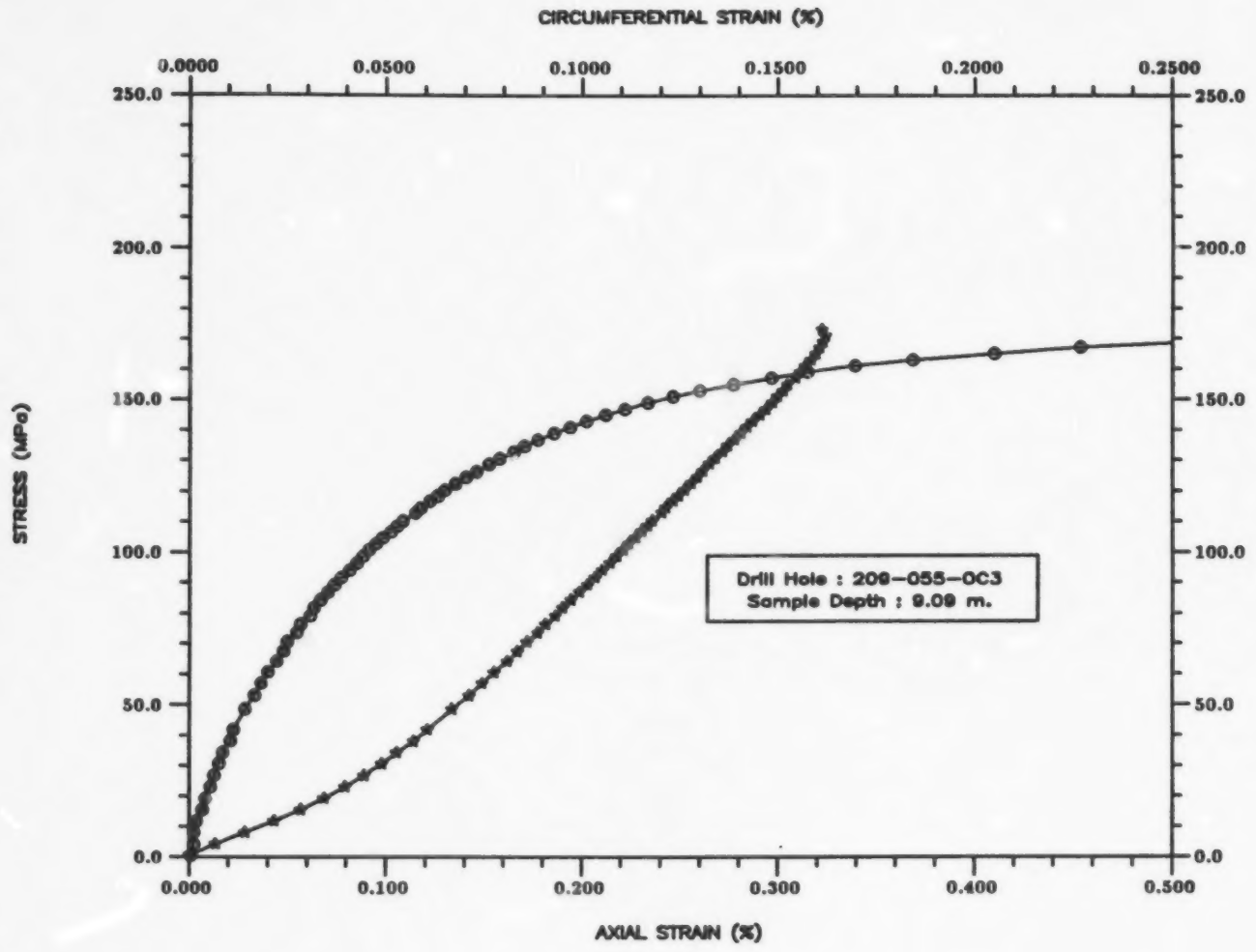

Figure 60: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen

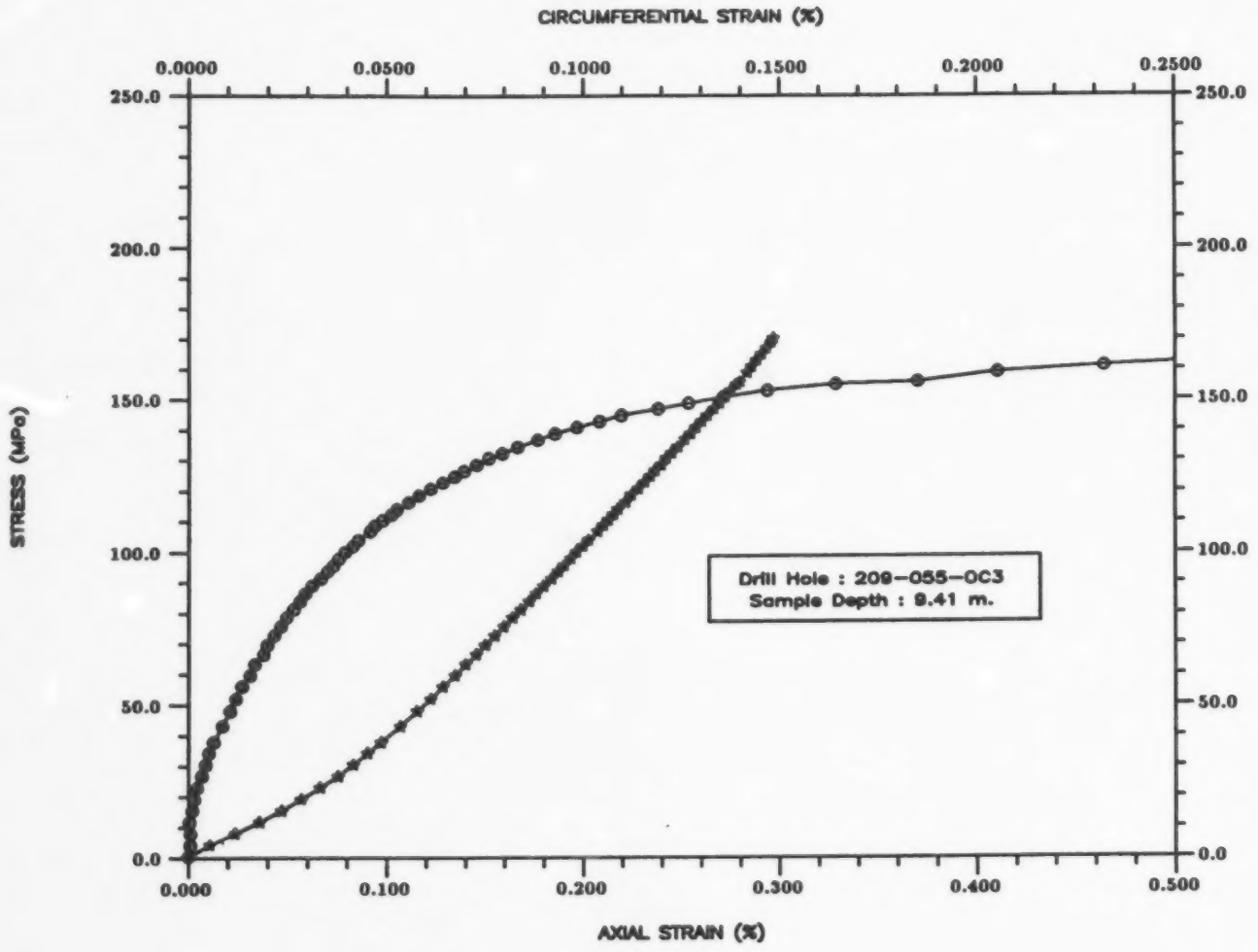

Figure 61: Axial and Circumferential Stress/Strain Curve, Scale Effects Specimen